OCEAN Challenge

Challenger Expedition

150th Anniversary

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Atlantification of the Arctic • How new science can boost coral populations • Mysterious sponge beds Organised crime is driving the vaquita to extinction • • The books that have inspired us

Vol.26, No.1

OCEAN Challenge

The Challenger Society for Marine Science

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The views expressed in *Ocean Challenge* are those of the authors and do not necessarily reflect those of the Challenger Society or the Editor.

SCOPE AND AIMS
Ocean Challenge aims to keep its readers up to date with what is happening in oceanography in the UK and the rest of Europe. By covering the whole range of marine-related sciences in an accessible style it should be valuable both to specialist oceanographers who wish to broaden their knowledge of marine sciences, and to informed lay persons who are concerned about the oceanic environment.

NB *Ocean Challenge* can be downloaded from the Challenger Society website free of charge, but members can opt to receive printed copies.

For more information about the Society, or for queries concerning individual or library subscriptions to *Ocean Challenge*, please see the Challenger Society website (www.challenger-society.org.uk)

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OCEAN Challenge

The Challenger Society for Marine Science

The Magazine of the
Challenger Society for Marine Science

SOME INFORMATION ABOUT THE CHALLENGER SOCIETY

The Society's objectives are:

To advance the study of marine science through research and education

To encourage two-way collaboration between the marine science research base and industry/ commerce

To disseminate knowledge of marine science with a view to encouraging a wider interest in the study of the seas and an awareness of the need for their proper management

To contribute to public debate and government policy on the development of marine science

The Society aims to achieve these objectives through a range of activities:

Holding regular scientific meetings covering all aspects of marine science

Setting up specialist groups in different disciplines to provide a forum for discussion

Publishing news of the activities of the Society and of the world of marine science

Membership provides the following benefits:

An opportunity to attend, at reduced rates, the biennial UK Marine Science Conference and a range of other scientific meetings supported by the Society (funding support may be available)

Receipt of our electronic newsletter *Challenger Wave* which carries topical marine science news, and information about jobs, conferences, meetings, courses and seminars

The Challenger Society website is
www.challenger-society.org.uk

MEMBERSHIP SUBSCRIPTIONS

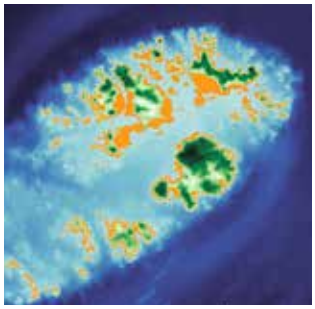
The annual subscription is £50 (£25 for students in the UK only). If you would like to join the Society or obtain further information, see the website (given above).

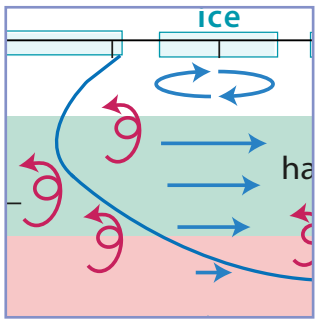
COUNCIL FOR THE CHALLENGER SOCIETY

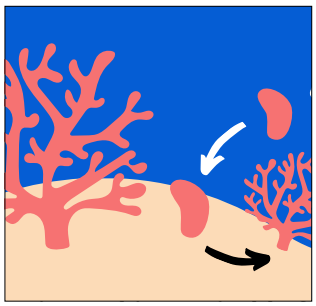
ADVICE TO AUTHORS

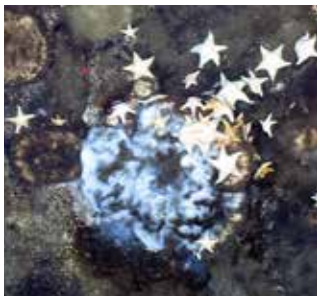
Articles for *Ocean Challenge* can be on any aspect of oceanography. They should be written in an accessible style with a minimum of jargon and avoiding the use of references. For further information (including our 'Guidance for Authors') please contact the Editor: Angela Colling, Aurora Lodge, The Level, Dittisham, Dartmouth, Devon, TQ6 0ES, UK.

Tel. +44-(0)1803-722513 AngelaMColling@gmail.com









Most of the maps and diagrams were drawn by The ArtWorks.

The cover and heading graphics were designed by Ann Aldred.

Cover image:
HMS Challenger *off the southern tip of the Kerguelen Islands*

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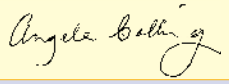
Message from the Editor

I must begin by apologising that this issue has fewer pages than usual – the flow of copy is still being impacted by Covid-19, because would-be authors are still trying to catch up with tasks that were delayed by the pandemic.

Despite the shortness of the issue, I hope you will enjoy its content. As often happens, themes have emerged in several otherwise unconnected articles, and this time, the recurring themes are the value of the science of genetics, and the role of microbiomes within host animals. By chance, there is more biology than usual in this isssue – If you feel that your own discipline is being under-represented, you know what to do! (Our *Advice for Authors* can be found on the Challenger Society website.)

NB We have a new feature, about books that have influenced our careers as marine scientists, and we very much hope you will contribute to this for future issues.



Challenger Medal Awards for 2020 and 2022

The Challenger Society is delighted to announce the delayed award of the 2020 Challenger Medal to Prof. Alberto Naveira Garabato, and the award of the 2022 Challenger Medal to Prof. Carol Robinson. Both will be presenting their Award Lectures at the forthcoming Challenger Society Conference.

Alberto's innovative and paradigm-shifting science has shone new light on ocean mixing and ocean circulation, and their relevance to the functioning of the Earth System. One of his major achievments was stimulating the creation of the UK–US Diapycnal Mixing Experiment in the Southern Ocean (DIMES), for which he is the UK lead.

A key aspect of Carol's career has been her involvement and leadership in the coordination of marine science, within and across institutions and national boundaries. Carol's determnation has been a crucial factor in the success of the long-running Atlantic Meridional Transect (AMT) programme. Her many important leadership roles include chairing the Scientific Steering Committee of IMBeR (Integrated Marine Biosphere Research) since 2016.

Challenger Society AGM

15 September, 2:00 p.m.

We are holding the event virtually on Zoom. The AGM will cover the reports from the President and Council portfolio holders from 2021, and handovers of Council positions.

Please join us. You can register for the event at https://www.eventbrite.co.uk/e/challenger-society-agm-tickets-387990318487

We look forward to seeing you there.

Challenger 150 Anniversary Photographic Prize

For the 2022 Challenger Society Conference Photo Competition, you are invited to submit photographs on the theme of 'Ocean Challenges', which you can interpret in any way you like.
We are looking for images that are beautiful, impressive, evocative, amusing, quirky, entertaining – anything that you feel reflects 'Ocean Challenges'.

The winner will be decided by the outgoing President and the President Elect, and the winning image will earn its photographer a prize of £100.
You may submit up to three photographs.

For more information and to submit your photo(s) see: https://docs.google.com/forms/d/1HYn9fQYhMneBmnlo7mscIcY2BugYYF_AoeRsrxpH04/edit?usp=sharing Entries must arrive by 8 September.

Photos should not have been taken for commercial purposes, or have received any previous award. Images should not have been significantly altered digitally (e.g. using Photoshop). They need to be at sufficiently high resolution to look good when printed, not just on screen. This means that the file size should be around 1 Mb or more, not tens of kb.

Photos may be used in future publications of the Society, with the owner's permission.

NB The competition is only open to members of the Society.

Can You Produce Winning Words ?

As for many previous Challenger Society Conferences, a prize will be awarded for the best report of the Conference, which will be published in *Ocean Challenge*.

The report should be your personal impression of the meeting – both science and social aspects, highlights and lowlights – rather than a blow-by-blow report. The emphasis should be on lively writing and good communication.

Entries should be sent to the Editor of *Ocean Challenge* AngelaMColling@gmail.com by 10 October, and be about 1000 words long.

The writer of the best report will receive a cheque for £100. Past wnners have included the first Chief Editor of *Nature Geoscience*, so you would be in good company!

Plant and bacterial 'giants' found in coastal environments

Oldest and largest photosynthesisers

Shark Bay in Western Australia is famous amongst Earth scientists for its 3.45-billion-year-old stromatolites – fossilised mounds made of layers of sediment and photosynthesising organisms including cyanobacteria. Stromatolites are the oldest known fossil records of life on Earth, but in a few places, including Shark Bay, they are still forming.

Shark Bay now has another claim to fame. Australian researchers wanted to know how genetically diverse the *Posidonia australis* seagrass meadows in Shark Bay were, and hence which plants should be collected for seagrass restoration. Seagrass is a flowering plant which reproduces sexually (producing seeds), helping them generate new gene combinations and genetic diversity, and by extending their rhizomes, producing clones.

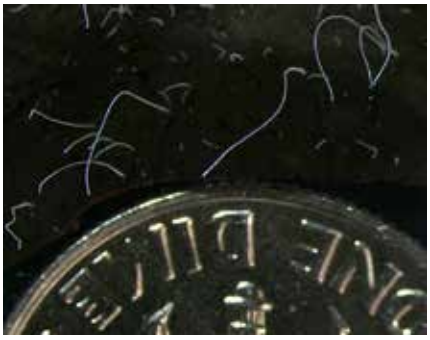
The researchers sampled seagrass shoots from across Shark Bay's highly variable environments and generated a 'fingerprint' using 18 000 genetic markers. They were amazed to discover that most of the shoots came from one single plant that had expanded over an area of 200 km^2, making it the largest known plant on Earth.

Significantly the plant is a polyploid, which means that it received 100% of the genome from each parent, rather than sharing 50%, doubling the number of chromosomes. Polyploid plants often live in places with extreme environmental conditions, and are often sterile. The original *P. australis* seedling probably took root in shallow water after Shark Bay began to flood thousands of years ago, and subsequently expanded into newly submerged and varied habitats.

A magnificiently large bacterium

When the white threads of *Thiomargarita magnifica* were first spotted on rotting leaves in the mangroves of Guadeloupe, it was thought they might be a kind of fungus. But each thread was an individual single-celled sulfur-oxidizing bacterium; at up to a centimetre in length, *T. magnifica* is 50 times bigger than any other bacterium yet discovered.

All previously described 'giant' bacteria (10s–100s µm) are polyploid, with tens to tens of thousands of genome copies dispersed throughout the cell. This species was found to have *half a million* copies of a very large genome. Furthermore, its genetic material is contained in membrane-bound granules; prokaryotes (bacteria and archaea) are traditionally distinguished from eukaryotes by their genetic material being spread throughout the cell, rather than contained within a membrane-bound nucleus.



Filaments of Thiomargarita magnifica *alongside a US 10-cent coin. Although segmented, each filament consists of a single cell, with a morphology resembling that of bacteria found at deep-sea methane seeps. (Photo: Tomas Tyml; © The Regents of the University of California, Lawrence Berkeley National Laboratory)*

Ed.

For more, see:

Edgeloe, J.M. *et al.* (2022) Extensive polyploid clonality was a successful strategy for seagrass to expand into a newly submerged environment. *Proc. Roy. Soc. B.* doi: 10.1098/rspb.2022.0538

Volland, J.-M. *et al.* (2022) *Science* **376**, 1453–8. doi: 10.1038/d41586-022-01757-1

Stepping Stones to a successful career

Reasons to apply for a Challenger Society Early Career Bursary

The Stepping Stones Bursary scheme is designed to support career development for members of the UK marine science research community currently without employment (for how to apply, see p.5). Below, a recent beneficiary of the award explains how he used the Bursary to help move his career forward.

Using a Stepping Stones Bursary to fill the Ph.D / postdoc gap **Richard Sims**

I am an early-career researcher whose work focusses on the flow of CO_2 between the ocean and atmosphere. After completing my Ph.D at Plymouth Marine Laboratory, in summer 2018 I travelled to Newcastle to present my work at the Challenger Society conference. My presentation at the meeting was well received, and afterwards Dr Jamie Shutler encouraged me to apply for the Stepping Stones Bursary to complete a project with him at the University of Exeter Penryn campus.

I applied for the Bursary hoping to learn how to use the open source Fluxengine modelling toolbox, developed by Jamie's team at Penryn, in my research into air–sea fluxes of CO_2. Like many researchers coming straight out of their Ph.Ds, I had little or no experience of independently applying for external funding. Writing a justification for funds to enable me to complete a piece of work was therefore an extremely valuable experience, and it has subsequently helped me when applying for funding opportunities.

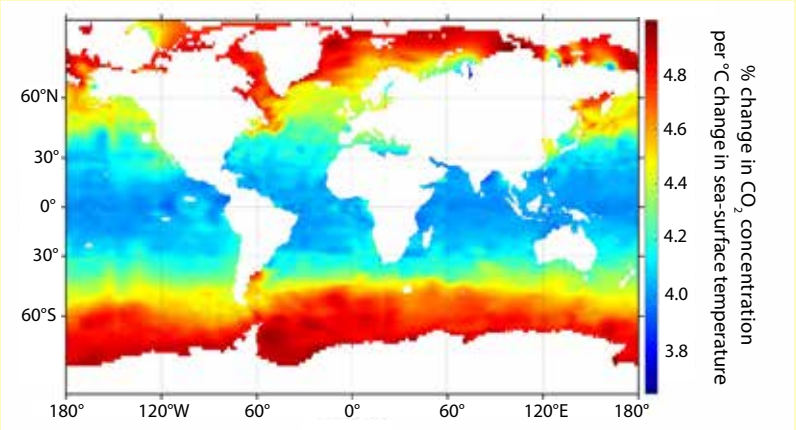
My second application for the Bursary was successful and I was able to use the funds to pay for a visit to Penryn in January 2019. During my time in Penryn I was able to build theoretical maps of the effect of sea-surface temperature on the concentration of CO_2 in surface waters (Figure 1), and hence, by using the Fluxengine, the effect on estimates of sea-surface temperature on global fluxes of CO_2. As part of this research I tested the impact of using a fixed 4.33% change in CO_2 concentration per degree change in sea-surface temperature (cf. vertical axis in Figure 1) in my calculation of CO_2 concentrations in surface seawater and then, using the Fluxengine, the air–sea flux. Having mainly worked on cruise data before, this was a great experience for me as I was able to scale up my research to the global scale for the first time.

Richard on RV Martin Bergmann in Icebreaker Channel in the North West Passage, during his postdoc in Calgary. Here he is connecting the CTD to the computer to retrieve the data from the last cast. (Photo: Neha Acharya-Patel/ Arctic Research Foundation)

The time spent in Penryn was a great opportunity to develop ideas I'd had during my Ph.D but did not have the skills or time to explore, and enabled me to remain engaged in research between my Ph.D and my first postdoc at the University of Calgary.

The decision to apply for the Bursary has continued to pay off. Two years after receiving the funds, I was employed as Jamie's postdoc in Penryn. As it was the middle of the pandemic and there were no opportunities to visit Penryn beforehand, having had the experience of working with Jamie and team proved invaluable. Since joining the lab I have already been able to write a first-authored paper with people from Jamie's team who I first met during my original visit to Penryn.

Percentage change in the CO_2 concentration of the surface ocean per degree change in sea-surface temperature, calculated using the CO2SYS toolbox and the surface-gridded total alkalinity and dissolved inorganic carbon datasets from the Global Ocean Data Analysis Project (GLODAP).



Richard on the ice in Cambridge Bay in the Kitikmeot Region of Nunavut, Canada, in May 2019. Richard and colleagues were taking sea-ice cores in order to melt them and measure the total alkalinity of the ice and dissolved inorganic carbon content; they were also were deploying an ice-tethered tilt current meter. (Photo: Zoe Walker)

I am currently using the Fluxengine to compute the impact of tropical cyclones on the atmosphere–ocean exchange of CO_2. I will present my first piece of work using the Fluxengine at the 8th International Symposium on Gas Transfer at Water Surfaces in Plymouth this year (2022). I also plan to see the project that was funded by the Stepping Stones Bursary through to completion with the aim of getting the results published later this year.

I would encourage other early-career researchers to apply for the Bursary, especially as its flexibility means that it can be used in many different ways and the funding is upfront and not conditional on any research output. The Bursary helped me learn new research skills and eventually helped me secure a postdoc which has benefitted my career immensely.

Richard is currently at the University of Exeter, where his research focusses on CO_2 in the surface ocean, and the atmosphere–ocean flux of CO_2. Richard enjoys going to sea to make observations but is also interested in how autonomous systems and big data can help us better understand the oceanic carbon system. R.Sims2@exeter.ac.uk

How to apply for a Stepping Stones Early Career Bursary

Stepping Stones bursaries are designed to support career development for members of the UK marine science research community who are not employed. Applications are not accepted from researchers holding permanent positions, but those on fixed-term contracts may apply up to three months before the end of their contract.

Individuals may receive only one bursary in any three-year period and the maximum amount that any individual can be allocated in any one funding round is £1000. Bursaries can be used for research-related activities which could enhance career prospects including, but not limited to, travel, collaborative visits, laboratory time, fieldwork and conference participation. It cannot be used to pay salary. The Society aims to fund four bursaries per year, and applications will be considered quarterly (deadlines: 15 February, 15 May, 15 August and 15 November).

The application form and full guidance notes for applicants can be found on the Challenger Society website.
https://www.challenger-society.org.uk/Stepping_Stones
Applications should be sent to Sophie Wilmes (s.wilmes@bangor.ac.uk).

See the Challenger Society website for other awards and grants that are available, including Travel Awards and the new Virtual Conference Award which aims to cover the costs of registration and administration involved in attending virtual conferences, and the Chris Daniels Early Career grants which aim to provide opportunities for motivated early-career researchers (ECRs) to create or establish a forum to discuss specific challenges and resources relevant to ECRs in the field of marine science.

Death of David Pugh

Friends and colleagues of David Pugh were saddened to learn of his death on 2 August.

David's personal scientific research was primarily focussed on sea level and tides, but he also had various roles in national science leadership and administration for NERC and notably for the Inter-Agency Committee for Marine Science and Technology.

He held important roles internationally. He was President of the Intergovernmental Oceanographic Commission (IOC) of UNESCO (2003–2007), Director of the Permanent Service for Mean Sea level (PSMSL) and founding Chairman of the IOC global sea level network, GLOSS.

There will be a tribute to David in the next issue of *Ocean Challenge*.

Some dos and don'ts for posters and presentations

If you have your eye on the prizes to be won for posters and talks at the Challenger Society Anniversary Conference, here are some tips. The poster prize honours Cath Allen, a researcher in fluid dynamics at the University of Lancaster, who died in 1991. The Challenger Society introduced the prize to combat the idea that contributing to a conference poster session is a second best alternative to delivering a paper, even though a poster needs to be at least as well thought-out as a talk. The prize for the best talk honours Norman Heaps, a shelf-sea modeller who died in 1986. He was a particularly clear speaker, with an enthusiastic, lively and entertaining way of delivering a talk.

The Cath Allen Poster Prize

- A poster is a chance to use your skill in presentation of data, in layout, and in distilling the essence of your message. **It is not an abbreviated paper**.
- **A poster needs to be attractive**, with an interesting title that is visible from a distance. If a poster doesn't draw attention to itself, it could be overlooked, and all the work put into it could be wasted.
- **A poster needs to be easily readable**, and not just by someone standing really close to it. For the main text, take care to choose a clear type-face at sensible point size. Avoid long complex sentences.
- **Avoid large slabs of text** and overlong line-lengths; the optimal line-length for readability is considered to be 50–65 characters per line, including spaces. For consistent spacing between words, use unjustified text.
- **Ensure your diagrams are large enough** to be seen clearly, and that the line weights of graphs etc. aren't too spindly.
- **Ensure that you have explained your symbols and acronyms,** and have put scales on figures if necessary.
- **Try not to have more than about five figures** (diagrams and photos). Remember that a well-chosen picture can be worth a thousand words.
- D**iagrams need to be close to the text** that relates to them, **or very easily found**.
- **Make use of colour** to enliven the poster and help direct the reader where to look.
- **Don't be tempted into over-complicating the appearance of the poster**, and obscuring your message.
- **Try to convey why your research is so exciting**.
- **Be there by your poster to answer questions**.

The Norman Heaps Prize

- **Time your talk beforehand.** There is nothing more upsetting than having to leave the podium without getting to your conclusion.
- **Beware of overload**. It's not advisable to have more than about half-a-dozen pieces of 'hard' information (diagrams, maps, tables) per 15 mins of presentation. **That's still only 2.5. minutes per picture.** (This doesn't preclude any scene-setting photos.)
- Don't forget that **your time slot includes** 2–3 minutes for **questions.**
- Everyone uses their Powerpoint slides as memory prompts, but **try not to find youself just reading from them or you will lose spontaneity**.
- In particular, reading through introductory slides that show the title, the aims, methods, results and even conclusions, takes up valuable time and isn't necessary, as the Chair will have already introduced you, and the audience has the list of abstracts. **If you are determined to have an introductory slide, make it brief and interesting**.
- Your results may be fascinating, but that's irrelevant if they can't be read from further back than the first two rows. **Graphs and diagrams are easier for an audience to take in than tables**. If you do use tables, highlight the numbers you are talking about.
- **Make use of colour** to enliven your graphics and help convey your storyline.
- **Use variety – switch between text, diagrams and photos**. If you use visuals from a number of sources, ensure that they use the same conventions for symbols etc.
- **Remember who your audience are**. Challenger conferences are attended by marine scientists from all disciplines, each with their own vocabulary, so try to explain any specialist terms so that everyone can follow your talk.
- **Try to convey why your research is so exciting**.

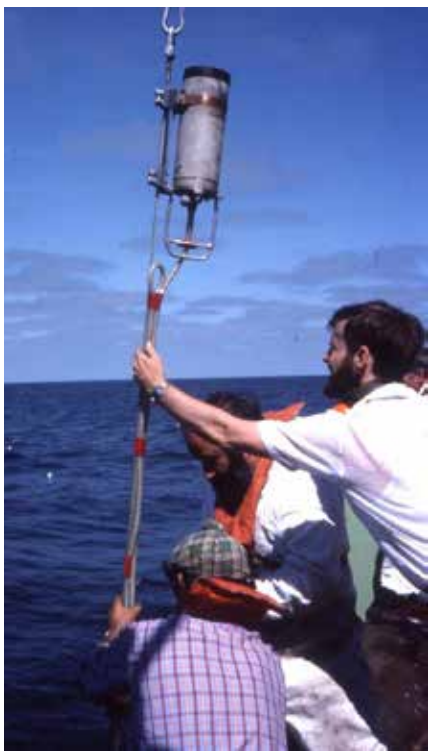
A tribute to Raymond Pollard: an influential and inspirational oceanographer

In December 2021, the National Oceanography Centre was deeply saddened to learn of the death of Raymond Pollard. Raymond was a towering figure in oceanography and was a major force in the development of the discipline; he inspired and mentored many young scientists.

Raymond completed an honours degree in mathematics at the University of Cape Town before studying at Cambridge University for his doctorate. He followed his thesis, on the theory of near-surface inertial oscillations, by a period with the Woods Hole Buoy Group, making the first high-quality observations of the structure of inertial oscillations and their propagation of wind energy into the upper ocean. Later, he returned to the UK, first to the University of Southampton and then to the Institute of Oceanographic Sciences (IOS), Wormley, in 1976.

Raymond's work exemplified the transition to big cooperative programmes and his early career saw leadership of the multinational JASIN (Joint Air–Sea Interaction)

Raymond attaching a thermistor chain to the mooring wire during Discovery *Cruise 86 under John Swallow. It was a precursor cruise for the main JASIN experiment in 1978, the year after Raymond joined IOS. (Photo provided by John Gould)*



Programme involving multi-ship and aircraft studies off north-west Scotland. He went on to lead the UK contribution to WOCE (World Ocean Circulation Experiment) and numerous other major sea-going expeditions, not least around the Crozet Islands and in the Southern Ocean and the south-west Indian Ocean. His interest in mesoscale phenomena like ocean eddies stimulated a strong and lasting collaboration with biological oceanographers linking the physics of mesoscale upwelling processes to nutrient injection into surface waters and the associated space–time patchiness of oceanic plankton.

The ocean mesoscale (10s–100s km, and days to weeks) required new measurement techniques for sampling at the relevant scales. Raymond was an innovator, and he played a crucial role in the development and use of towed undulating CTDs (*Seasoar* particularly); he was an early user of Acoustic Doppler Current Profilers (ADCPs) from which he pioneered a technique for extracting vertical velocities by inference from the horizontal fields; and he played a critical role in bringing scientific computing on board ships, notably RRS *Discovery*, to process the vast quantities of data quickly.

The new, rapid, initial analysis and interpretation of data at sea was very important for the science but it had effects beyond that. Many of us remember several 'straight off the ship' conference presentations by Raymond where he would arrive from RRS *Discovery* keen to present his first plots, bringing the immediacy, insight and excitement of new results to audiences in an inspiring way. Raymond played a critical role in forming and developing the big scientific teams we work in today.

He spearheaded the move to Southampton when in 1989 he led the formation of the James Rennell Centre for Ocean Circulation, set up to deliver WOCE, which integrated observations and ocean modelling. The new Centre was the vanguard in the move of IOS to Southampton, relocating from Wormley to the Chilworth Science Park before moving into the then newly built Southampton Oceanography Centre in 1995. Raymond spent many years leading multidisciplinary and multinational research into the way physical zonation in the ocean controls the broad-scale distribution of biological phenomena. Questions raised by previous research led to the Crozet Experiment (CROZEX), a major UK field programme that addressed the role of natural iron fertilisation on carbon export in the Southern Ocean.

Raymond inspecting the ice conditions during the first Marine Productivity Programme cruise in the Irminger Basin, April 2002. (By courtesy of Alex Mustard)

Raymond was a great scientist, fine colleague, mentor and inspiration to many. His loss will be felt by his former colleagues in the UK and around the world, and all those he worked with at sea including mariners, technicians and engineers. Raymond had huge energy and wanted to extract every drop of information out of the data and days at sea; sometimes he was hard to keep up with. As a colleague at the National Oceanography Centre (NOC) has said, his way of working at sea provides a fine exemplar even today: 'extreme attention to detail, maximising the time at sea, but at the same time being cheerful, kind, patient and understanding with people; all these were taught to us by Raymond.'

In his latter period at Wormley and while at Southampton, Raymond worked closely with his wife Jane Read, and their strong bond in science and companionship meant that they made a formidable team. Both had a huge influence on younger colleagues. Sadly, Jane also passed away in August 2021.

Our thanks go to Raymond's colleagues whose contributions make up this tribute.

Adapting to survive – in the Bronze Age and today

Legend has it that the land of Lyonesse was engulfed by the sea in a single night during a dreadful storm. This mythical land lay somewhere between Brittany and Cornwall, much like today's Isles of Scilly. It is rumoured that fragments of masonry from Lyonesse turn up in the hauls of Cornish fishermen even today.

The legend of Lyonesse predates even the time of KIng Arthur's putative rule, but the story of island communities coping with rising sea level off south-west Britain starts millennia before that. Research carried out by an international team, from the UK, Canada and Hong Kong, and published in *Science Advances* (see Further Reading), sheds new light on how people adapted as islands like Lyonesse were lost to the sea.

Scilly: from island to archipelago

Today the Isles of Scilly are a low-lying archipelago, less than 50 km from the coast of Cornwall. But around 21 000 years ago Scilly was not an island at all, but was joined to mainland Cornwall by a land bridge. At this time, towards the end of the Last Glacial Maximum,* a large ice sheet still occupied Scotland, Ireland and much of northern Britain, and south-east Britain was still connected to continental Europe. People were able to travel across Europe along with the last of the large ice-age mammals (woolly rhinos, mammoths and cave lions), unhindered by wide seaways.

*The Last Glacial Maximum is the time in the last glacial period when global ice sheets were at their maximum extent, which was between 29 000 and 19 000 years ago.

But with the retreat of the major ice sheets in northern Europe and North America, sea level around the world rose rapidly. Rates of sea-level rise around the south-west were higher than anywhere else in the British Isles, a response to the melting of ice sheets over more northerly parts of Britain and those elsewhere. This was not just because of meltwater being added to the global ocean: as the great weight of ice was removed, the crust it occupied started to rebound while the adjacent land to the south (which was bulging upward) started to sink. This process is still ongoing today – the land in south-west Britain is currently sinking by around 1 mm yr^{-1} while Scotland continues to rise.

By 12 000 years ago, Scilly had been separated from mainland Britain and was one single large island, nearly 140 km^2 in size (Figure 1). The researchers investigated how Scilly has changed since then, by analysing pollen records and the remains of microorganisms in submerged and fossilised peat and saltmarsh deposits. They used their data to recreate how the coastline and the vegetation cover of the landscape changed, as well as to study the population dynamics across Scilly and the wider region.

The research showed that a high rate of relative* sea-level rise (~2.8 mm yr^{-1}) continued around Scilly from around 7000 years ago up until about 4500 years ago, by which time the one large island had lost ~100 km^2 of land and had become an archipelago (Figure 1). The rate of sea-level rise then decreased: only the ice sheets over Greenland and Antarctica remained, and the rate at which the crust in south-west Britain was sinking was decreasing. Nevertheless, Scilly was still transforming rapidly because the coastline was low-lying, and as sea level continued to rise at the modest rate of 1 mm yr^{-1}, land area was being lost by around 10 000 m^2 a year and dramatic coastal changes were taking place.

People on the Scillies

So were humans present on Scilly at the time? There is no hard archaeological evidence for permanent settlement before 4500 years ago but the new 12 000-year-long record of environmental change revealed that there was oak woodland across Scilly from 9000 years ago, and that this abruptly vanished 2000 years later, suggesting that humans were clearing forest for hunting and resources (Figure 2). Flint microliths indicate that people were visiting Scilly during the Neolithic (6000 to 4500 years ago), and evidence from pollen of land disturbance (Figure 2) and of fire, from charcoal, as well as archaeological finds across the islands, show that by the Late Neolithic local populations were actively managing the landscape. Crops were being grown to some extent, and animals were being kept (see submerged field boundaries in Figure 3). The research thus adds to the growing body of evidence for a permanent human presence on Scilly beginning shortly after 4500 years ago, right at the end of the Neolithic and the beginning of the Early Bronze Age.

On Scilly at this time, there was a significant increase in human acitivity. The Bronze Age is marked by an abundance of material culture in the form of worked flints, pottery and vessels. Even more remarkable was the number of stone structures. There are over 600 Bronze Age cairns, standing stones, entrance graves and other monuments across Scilly, which by then had an area of less than 30 km^2; there may have been more, now lost to the sea. Bronze Age archaeology on Scilly is richer than for any other period through time.

*Relative sea-level rise means the rise in sea-level relative to a specific landmass, in this case the Scillies, which were sinking as absolute (global) sea-level rose.

St Michael's Mount, a tidal island off Cornwall, said to be near the legendary land of Lyonesse

(Photo: @benjaminelliott via https://unsplash.com/photos/ sg7zgMb3OQY)

Back to the sunset bound of Lyonesse –
A land of old upheaven from the abyss
By fire, to sink into the abyss again;
Where fragments of forgotten peoples dwelt ...

Idylls of the King
Alfred Lord Tennyson (1859)

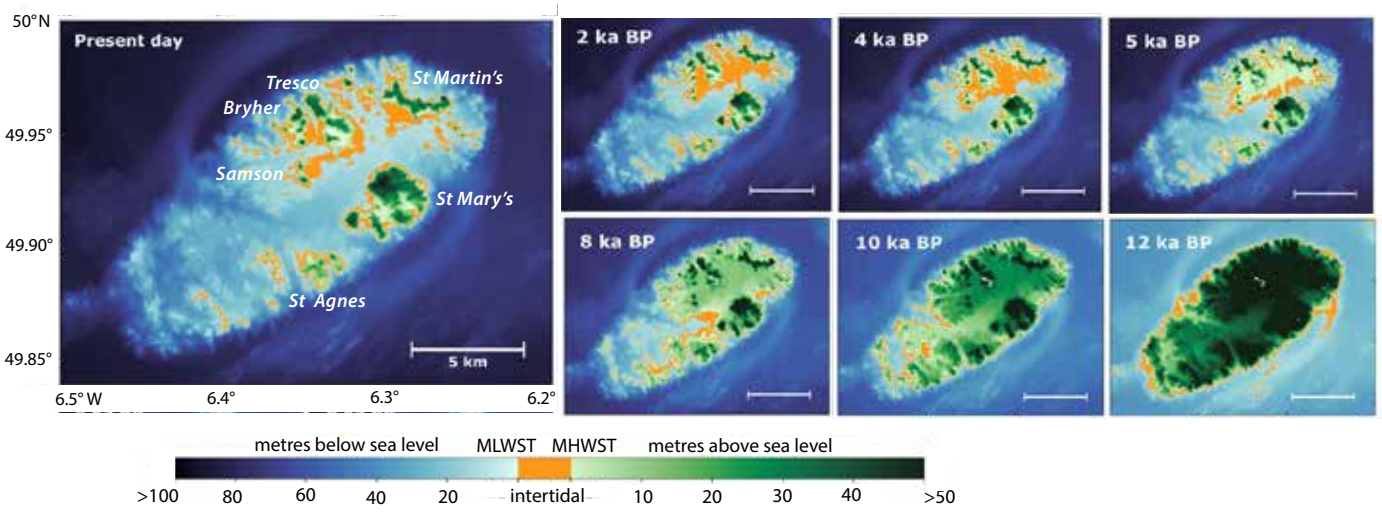


Figure 1 *The Isles of Scilly – then and now. Modelled changes in topography (green), bathymetry (blue) and intertidal zone (orange); in the key, MLWST and MHWST = mean low water spring tide and mean high water spring tide. Over the 12 000 years, total land area decreased from ~140 km² to ~25 km². Despite a decrease in the rate of sea-level rise around 4.5 ka, between 5 and 4 ka 36% of the land was lost and an extensive intertidal zone was created. Today, the Scillies consist of 145 islands and rocky islets. (Maps courtesy of Sophie Ward; see also Barnett* et al. *(2020) in Further Reading)*

A fast-changing environment

During this time of rising seas, the available living space was decreasing and the coastal environment was changing year after year. The changes would have been alarming – over the course of 50 years land area would have decreased by more than 500 000 m², and knowledge passed down through the community, extending back over perhaps a few hundred years, would have re-enforced awareness of the changes. However, the rich archaeology indicates that there was nevertheless a powerful incentive for Bronze Age communities to remain on Scilly. This suggests that cultural adaptation, rather than physical flight, was the preferred solution for the inhabitants of Scilly during this time.

Research from other parts of the world (such as the Yangtze coastal plain in east China) has shown how some Neolithic communities were forced to flee sites of coastal inundation. We might never know why the early Scillonians decided stay put, but it is likely that the changes they were experiencing were not entirely negative. About half of the lost land was turning into intertidal regions (orange in Figure 1) and between 5000 and 4000 years ago the total area of the intertidal zone across the archipelago nearly doubled, largely because the large north-eastern island became five separate islands joined only at low tide (Figure 1). New areas of rocky shore, saltmarsh and sedge meadows offered greater opportunities for foraging, fishing and wildfowl hunting. An increase in valuable food resources such as shellfish would have helped support a growing population.

Since the Bronze Age, the area of both land and intertidal zone on Scilly have been dwindling. However, as recently as the 11th century, the islands were still mostly joined at low water, and at very low spring tide today it is possible to walk across the sand between Bryher and Tresco. Scilly is still sometimes referred to as 'Ennor', which is a contraction of the Old Cornish for 'the land' or 'the great island'.

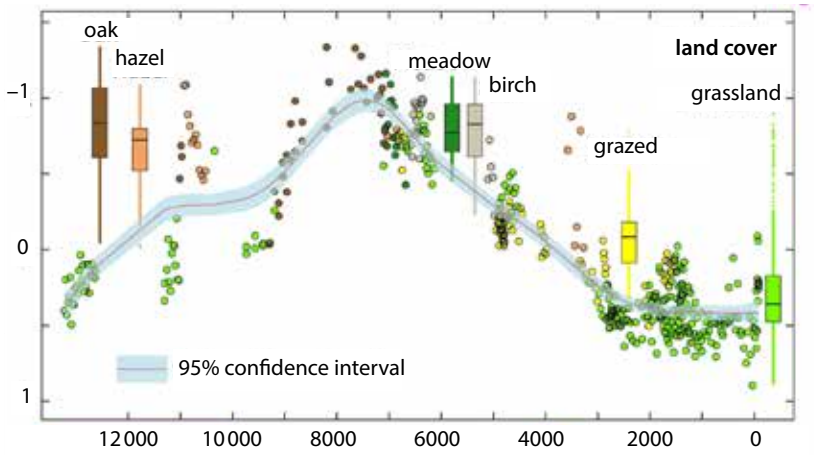


Figure 2 *The changing vegetation cover index for Scilly based on pollen data. There are no units on the vertical axis because data points are derived from a multivariate anaysis of plant community composition, with the vertical position and colours reflecting the dominant plant communities. The brown curve shows the trend of the change, and the labelled points for oak, hazel etc. show the error bars associated with data from each plant community. (Barnett* et al. *(2020); see Further Reading)*

After millennia of modest rates of sea-level rise (~ 1 mm yr⁻¹), sea level around the Isles of Scilly is now rising at ~ 3.6 mm yr⁻¹, in line with the rate of global mean sea-level rise. Like other coastal communities across the globe, Scillonians will have to face increased flooding and coastal erosion exacerbated by more frequent extreme weather events.

Figure 3 *Submerged prehistoric field boundaries off the coast of Samson Island in the Scillies.*

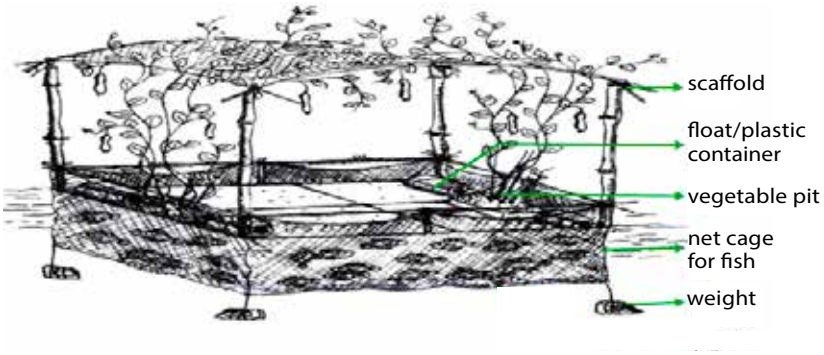


Figure 4 *In coastal Bangladesh, the combination of monsoon rains and rising sea level means that fields are regularly flooded.* ***Upper*** *Part of a floating farm where gourds and other food crops are grown. Traditionally, floating farms were made using rafts of buoyant plants (e.g. water hyacinth).* ***Lower*** *Continued sea-level rise means continued adaptation. As sea level rises, salt intrusion into estuaries means that growing certain crops becomes increasingly challenging. The sketch shows an example of how a floating garden could be combined with a fish farming enclosure.*

(Images: Practical Action practicalaction.org)

Adapting to survive today

In some instances, rising sea level can be accommodated; options include hard engineering solutions such as raising houses or diverting roads, building flood defences or land reclamation. Natural approaches, such as sand dune or mangrove restoration projects, are already being employed. An increasingly acceptable approach is managed retreat, allowing the sea to flood inland, generating natural and cost-effective storm-defence systems, improving biodiversity and ecosystem health, and – importantly – forming carbon sinks.

It is perhaps unlikely that today's rising seas will naturally result in new intertidal zones and resources capable of supporting growing populations, as may have been the case on the Isles of Scilly thousands of years ago. Nevertheless, coastal populations around the world are finding ways to cope with sea-level rise while generating new sources of food. One example is cultivation using floating farms which have long been used in Bangladesh and India, and are now being made more productive (Figure 4).

Building new habitats Coastal barriers made of oxyster beds are increasingly being used around the world, from Bangladesh to New Jersey. Oyster larvae will naturally settle on bags of old oyster shells or concrete structures. As the oyster beds establish, other organisms move into the new habitat. The oysters clean the water, and protect and encourage mangrove and/or seagrass beds on their landward side. In some locations they can trap sediment being carried down by rivers, countering erosion of the coastline. At present, the barriers grow upwards at rates that can match rates of sea-level rise. 'Living seawalls', constructed with increasing biodiversity in mind, are also becoming more common.

The above measures have the potential to be highly effective, at least in the short term, but well designed warning and early response systems, and provision of evacuation zones in response to the increased severity of events such as storm surges, are of ever-increasing importance.

The options available to small, often poor, island communities are limited. Thousands of inhabitants of Pacific Islands such as Vanuatu, Tuvalu and the Marshall Islands, have already relocated to other countries, abandoning much of importance to them culturally. The first country which will be completely destroyed by rising sea level is Kiribati, 33 atolls in the central Pacific. The Kiribati government has bought land in Fiji to grow crops and possibly even provide a home to the country's entire population if necessary. The World Bank has proposed that Australia and New Zealand should allow open migration of people displaced by sea-level rise from Kiribati and other Pacific islands. New Zealand is currently offering immigration to 75 Kiribatians a year.

Floating islands Coastal cities in the Netherlands, Germany and Denmark, already short of space, are well advanced in developing small floating islands, to accommodate offices, housing and leisure facilities. The world's largest floating office building, and a floating dairy farm, are in Rotterdam, 90% of which is below sea level.

There are plans for much bigger floating islands, intended to support entire small cities; one proposal is for floating islands in the Baltic Sea with housing for 50 000 people, but the most advanced plans are for Maldives Floating City in the Indian Ocean – the Maldives are predicted to be uninhabitable by 2100. The Maldives government has partnered with a developer from the Netherlands to create a floating city that will contain 5000 low-rise homes within a 200-hectare lagoon close to the capital. Construction is planned to begin later in 2022, and to be completed by 2027. It is hoped that up to 20 000 locals and foreigners could move in as early as 2024. Artificial coral reefs will be attached to the underside of the floating city to stimulate natural coral growth, providing new habitat for marine organisms alongside homes for people.

This article was inspired by, and partly draws on, 'Prehistoric communities off the coast of Britain embraced rising seas – what this means for today's island nations' by Sophie Ward, published on theconversation.com in 2020.

Ed.

Further reading

Barnett, R.L and 20 others (2020) Nonlinear landscape and cultural response to sea-level rise. *Sci. Adv.* **6** (45), eabb6376. doi: 10.1126/sciadv.abb6376

https://www.weforum.org/agenda/2022/08/living-seawalls-eco-engineering

Climate Change Scenario; Relocating a Vulnerable Coastal Community A simulation scenario by UNOSAT (2021) https://storymaps.arcgis.com/stories/47a1957a1c144b688c5d03b70a7da8d8

https://www.waterstudio.nl

Collating the past to inform the present and the future

Angus Atkinson, Head of Plymouth Marine Laboratory's Plankton Ecology Group, went back in time to the early RRS *Discovery* records to investigate what they could tell us about Antarctic krill. He spoke to Kelvin Boot.

'I love doing research because it's like detective work but without the blood. I like trying to find the little clues to how Nature works – clues that are often scattered, well hidden, but sometimes blindingly obvious yet ignored. For me, this quest often involves first thinking of ways to build really big datasets, for example piecing together multiple studies into a meta-analysis, or mining old historical datasets and compiling them to build long time series.'

Angus Atkinson (PML website)

The quote above relates to your work today, but where did it all start for you?

I grew up near the sea. I spent my first six years on Bardsea Island, off the coast of North Wales. Dad was farming sheep and fishing for lobsters, and I used to go out fishing with him, so my interest in the sea began at a very early age. We then moved to Plymouth where from the late 60s into the 1970s Dad joined his brother in demersal trawling. They then moved to mid-water trawling and I used to go out during the free-for-all of mackerel fishing when the fishery was badly managed and stocks were being over-fished; they were catching something like 100 tonnes of mackerel per night and selling them for fish meal. At the same time I often used to see the MBA's Sarsia *research vessel in Plymouth's Millbay Docks and that's when I decided I wanted to become a marine biologist. So that's what I did. My first degree was at Swansea where I especially enjoyed the practical aspect of field courses. That was benthic ecology fieldwork, but my first job, just after I graduated, was in pelagic ecology and plankton, at the British Antarctic Survey. It was my first trip to Antarctica that really set me alight, and I soon became fascinated with the whole subject of Antarctica and krill.*

That was in 1984. Did we know much about krill back then?

Yes, I think it was the 'golden age' of krill research. The fishery had expanded, and some of the largest catches were recorded before the break-up of the Soviet Union – I think about 500 000 tonnes per year. Those huge catches prompted intense research and a lot of publicity on krill in the 1980s. To begin with, I was working on smaller zooplankton, which at the time were definitely the second-class citizens, and my work was well below the radar until around 1996. I had been on a series of contracts, and with the fluctuations in BAS funding you never knew if your contracts were going to continue. Coincidentally 1996 was a poor year for the species I was working on, so I made the switch to krill, which led eventually to me becoming a full member of staff at BAS.

What was it about krill that made people want to catch it in such large quantities?

At the time, and it is still the case now, it was seen as an underexploited source of protein. Back then the idea was that you could feed the world on krill, as the total biomass of krill was thought to be around 500 million tonnes, far more than was being caught. It was seen as a bountiful and nutritious food resource. Indeed it is, but one challenge was that it was difficult to process for human consumption; the shells, the exoskeletons, proved particularly problematic as they have a very high fluoride content. Natural predators are superbly adapted to eating krill, but for humans the krill have to be de-fluorinated, and that was technically very difficult. It meant a lot of the catch went for fish meal and aquaculture feed stock, for example. More recently krill has undergone a renaissance as a source for Omega-3 and fatty-acid food supplements.

Back in the 90s, what was the main thrust of your research?

It was all to do with learning more about the basic ecology of the krill. In the mid to late 90s I was doing a lot of experimental work on krill, going on a lot of research cruises, to look at their feeding and energy budgets, how they overwinter, their life-cycle strategy – the basic understanding of krill and how they fit into the food web. I spent most of the time in the cold room of the RRV James Clark Ross *and the German research vessel RV* Polarstern*. That's where I met my future wife, over a tub of krill.*

Then came the change in my research. In 1999 I began to do more desk-based research, compiling all the existing literature data about the abundance of krill, collected from surveys. Most of the data had been collected from net samples trawled at fixed stations, so we would get that original source data from each net sample. So, I went from incubating krill in a cold room to collating data into a single database that we called KRILLBASE. That took about six years up to 2005.

The Discovery *Expeditions, carried out from the late 1920s to the 1930s, and a little more research post World War II, paid for by the whaling industry, produced a large amount of data on Antarctic krill. The researchers kept very good notes and the data were well annotated. It's all stored at the*

National Oceanography Centre library. It was these hand-written log sheets, complete with coffee stains and doodles, that formed the core of my investigations. Some of these were typed in an organised layout as shown in the photo, and this helped greatly.

A fantastic resource but it must have been a time-consuming project?

Yes, I spent much time in Southampton transcribing huge amounts of data onto a 20-column spreadsheet, with each row being a net sample. The basic information was how many krill per m^3 of water were there. Other columns gave details about location, date, gear type etc.

We were able to supplement the Discovery *data thanks to the help of colleagues working in their own countries, including the USA, Germany, South Africa, Russia, Japan, Ukraine, Australia and Italy. In all, about a dozen countries made available data from 15 000 net-hauls now spanning the period from 1926 to 2016 – a massive dataset. So more data, more spread in time and space and a more accurate picture of what was going on with Antarctic krill.*

Today the idea seems simple enough, but at the end of the 1990s it was more novel; it's an example of how important collating old datasets can be, and a very strong argument for maintaining long time series. Indeed, climate change has shown how important time series are. The interesting thing about KRILLBASE is that it was never designed as a time series – we have been able to build a time series from all the data sources so it's a compiled time series.

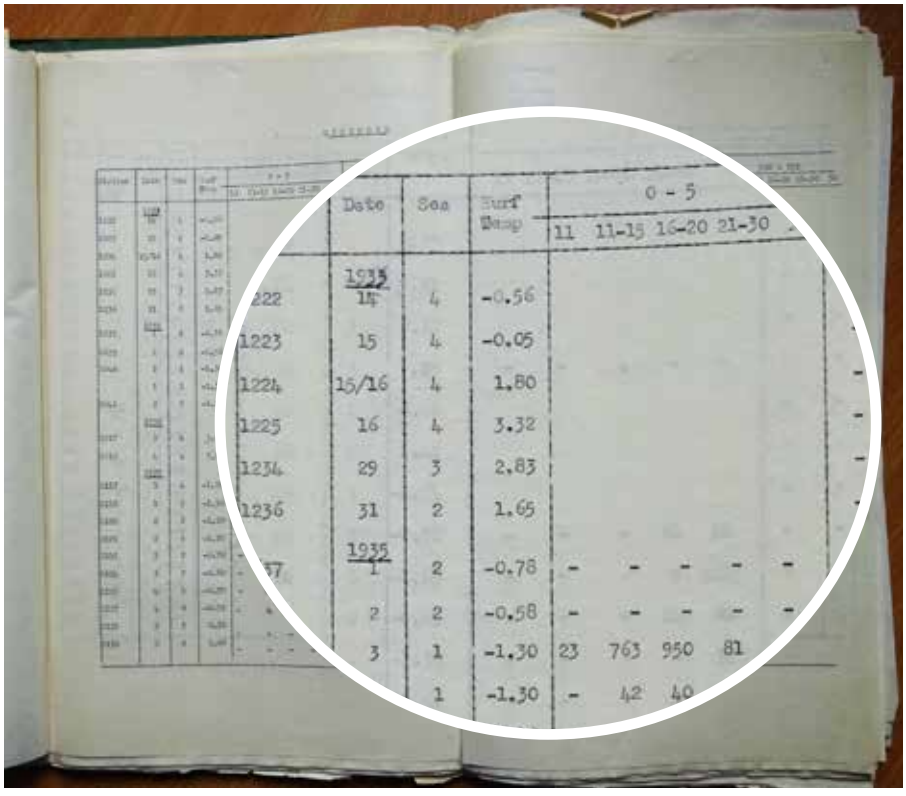
Today we have strict guidance as to how data should be collected and recorded. Did the long time period and the range of different sources cause problems for comparing like with like?

That's a really interesting point, because there has been a major controversy over our findings. The original surveys would have been carried out with various types of net and so we had to use statistical methods to take that into consideration and standardise the results. That enabled us to conclude that there was a decline in South West Atlantic krill from the 1970s through to this century. That was important because at the time the krill fishery was expanding and the climate was warming, posing a threat to the cold-water krill. The 2004 Nature *paper that presented these results has been cited over 1000 times, but not everyone agrees with the findings. As you can imagine, a decline in krill populations was not great news for the krill fishery. Because we were saying the stock had decreased, some conservation bodies began to question whether fishing for krill was sustainable, and criticised the management organisation, the Commission for the Conservation of Antarctic Living Resources (CCAMLR). The debate still rumbles on.*

And the fact that debate continues is a driver for more study and more data?

Exactly, but the ironic thing is that the funding for net surveys is dwindling as we move towards newer technologies. Krill biologists are currently debating how best to survey for krill, as we shift away from net sampling, which has been used for almost a century, to new methods which are hard to calibrate against the net method. Gliders, moorings and acoustic surveys aboard krill fishing vessels are all being discussed as a way forward. It is really difficult to compare the methods, but we need to do so and continue to monitor krill in a consistent way into the future.

A page from one of the Discovery *catch notebooks, for December in the years 1935–1937, with part enlarged. After columns for date, location and surface temperature, are columns for how many of each size category of krill were caught in the fixed depth hauls (0–5 m, 0–100 m, 100–250 m etc.).*



Has the distribution of Antarctic krill changed over time?

Krill are most abundant in the South West Atlantic sector, and within that sector there are some regions that hold more krill than others. What the records tell us is that with climatic warming there have been range changes; as the Antarctic warms, the isotherms move towards the Antarctic continent and the krill have moved about 1000 km south-west in response. The spawning grounds have also moved much closer to the continent, following the colder water. Mining the historical data has shown us that this has been happening. Each net sample is like a piece of a jigsaw puzzle, it's only when the data are brought together on a single spreadsheet that the picture emerges.

What else does KRILLBASE tell you?

It isn't just the time perspective that is important, KRILLBASE has also

enabled us to work out in some detail where krill live at different life stages, from the mesoscale to the circumpolar scale. In the South West Atlantic sector a lot of the krill are living over the continental shelf, or close by, on the continental slope. It's the juveniles that are strongly shelf-based while the larval krill are more oceanic, so the different life stages are partitioning the available habitat.

As the database has matured we have expanded it to include length–frequency data which reveal the population structure of krill, somewhat like a fisheries database where you have size as well as abundance data. That can give insights into population dynamics, such as when there has been a good spawning event, and we've seen that krill are getting bigger. That sounds like a positive thing but we speculate that it is possibly due to fewer krill surviving, with those that do survive being able to live longer and grow larger. Recently, larval data have also been added, and a database of total zooplankton biomass to run alongside – another example of pulling together data from old records.

Have you managed to find all the useful historical data? Or are there more sources out there for krill?

We started to get diminishing returns, but the main problem has been that funding for it has been difficult in recent years, so it's been relegated to being a 'spare-time' job and I have had to prioritise. With the larval data I was unable to stray beyond the South West Atlantic, and that's frustrating because not only do I really enjoy the data-collation aspect of my work, it has been, and continues to be useful. I think that by bringing the old Discovery *data together with that from other countries working in the Antarctic, and adding more recent data, we have got a pretty good picture of what krill do in the Antarctic. There may be other smaller datasets we haven't been able to interrogate but we are confident we can tell a good and reliable story.*

On a personal level, KRILLBASE has been the most exciting science of my career. You might collect a lot of data on one research cruise, but collating for KRILLBASE entailed putting data together from hundreds of cruises. For the length–frequency data, the number of krill measured was more than one million.

How important are krill for the Antarctic marine ecosystem?

It's a difficult question. If you think about the sheer biomass of krill, it's said to have the highest biomass of any non-farmed animal species, and similar to that of humans – it's massive. When you go to the Antarctic, you notice that many of the land-based species of predators have pink faeces, which is due to them eating krill. In a low-krill year the beaches can be littered with dead fur seal pups, and in really bad years the adult seal deaths also increase, such is their reliance on these small crustaceans.

Has KRILLBASE been used to inform studies on other animals, krill-eating whales, for example?

Yes, it's been accessed for a variety of uses. In 2017 the Worldwide Fund for Nature (WWF) gave us some funding to make our data more available and that has led to a number of studies on predators to work out where the food might be and how that correlates with where the predators are. Other, more krill-focussed studies have been looking at predicting where krill might be located a century into the future.

KRILLBASE is now freely accessible. It's stored at the Polar Data Centre at BAS, and so hopefully there will be more and more users.

Illustration of one of the short food chains for which the Southern Ocean is famous, with Antarctic krill eating diatoms and in turn preyed upon by gentoo penguins.

(Graphic by courtesy of Glynn Gorick)

If you are now intrigued by krill, see:

Atkinson. A., V. Siegel, E. Pakhomov and P. Rothery (2004) Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature* **432** (7013),100–103. doi: 10.1038/nature02996

Priddle, J, J. Watkins and E. Murphy (1993) Krill: the ecology of aggregation. *Ocean Challenge* **4** (3), 46–50

Sturm, K.-D. and K.-J. Hesse (2000) Chitin and chitosan – natural polymers from the sea. *Ocean Challenge* **10** (1), 20–24.

Tarling, G. and A. Atkinson (2009) Antarctic krill: an intriguing tale of ice and industry. *Ocean Challenge* **16** (3), 20–26.

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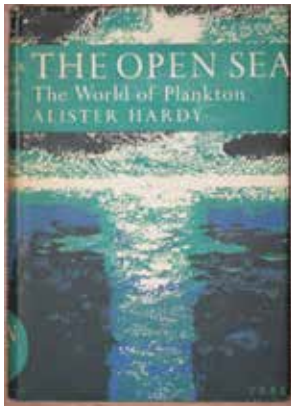
Books that have inspired us

This is the first in what we hope will be a series about books that have influenced our lives as marine scientists. To get things going, here are some choices by some *Ocean Challenge* Editorial Board members and long-time contributors to the publication.

The Open Sea: Its Natural History Part 1, The World of Plankton
by Sir Alister Hardy
Collins New Naturalist, 1956



Chosen by
Kelvin Boot, science communicator, and Peter Herring, marine biologist

Kelvin: No-one in my family remembers a day when I wasn't hooked on nature; every weekend we would wander the fields and lanes, streams and ponds in search of flowers, insects, and birds. Holidays were different, we would travel north to my grandparents in Northumberland, spending endless days on the deserted beaches. We caught sand eels, 'flatties' and jellyfish in the tidal pools while terns screamed overhead and gannets plummeted for fish. But it was back in Leicester that I had my epiphany. A regular Saturday morning haunt was the City Library; I would scour the shelves for another nature book but soon exhausted the supply in the children's library – the grown-ups' library beckoned. It was here that I chanced upon Sir Alister Hardy's *The World of Plankton*. I don't know if my chin hit the floor, or my eyes were like saucers, but this was a revelation. I had found Davy Jones' treasure chest, stacked with beautifully illustrated salty wonders.

But children were not allowed to borrow grown-up books – and what if someone else borrowed *Plankton* for weeks on end? I needed a plan. At the end of each reading session I would return the prized volume back to a different shelf. Alister Hardy had many interests but even he would have been surprised to find himself in cookery, classical music, politics or crime fiction. Each week I retrieved the book to soak up a bit more of the secret world populated with bizarre and mysterious life-forms, painted literally and figuratively by Hardy.

Later, I veered off the rails and became a museum palaeontologist (dead marine biology!), but I returned to marine science as a science communicator – I like to think that some of Hardy's style rubbed off. I never lost the fascination for hidden worlds and the telescoping of scale, kindled by Hardy's clear, enthusiastic writing.

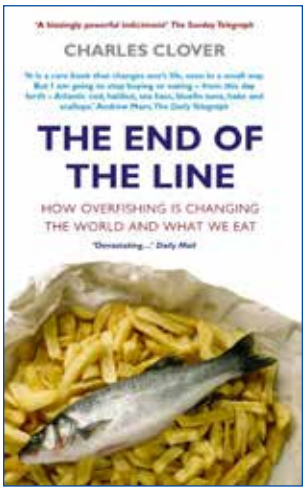
Peter: When you have little knowledge of a subject, opening a book by an expert can be either an exhilarating or an intimidating experience. For me, in my late teens, Alister Hardy's *The Open Sea: The World of Plankton* was eye-opening. Everything in it was fascinating. His very down-to-earth introduction on how to catch and observe plankton included the comment: 'Two modern inventions have altered all this: the Thermos flask and refrigerator.' Then there are his stunning watercolours of everything from diatoms to medusae, pteropods and anglerfish, done both in the lab and at sea on RRS *Discovery II*, sometimes sitting on the bowsprit! Many of the fine line drawings are his too, while D.P. Wilson's splendid black and white photographs complete the visual content.

The book appeared as No. 34 in the Collins New Naturalist series and was rapidly followed (1959) by the companion volume (No. 37) on *Fish and Fisheries*. They were first written as a single volume, but Hardy soon appreciated that splitting it into two would do the subjects more justice.

I confess that my copy of that second book still has its dust jacket, but *The World of Plankton* is thoroughly worn and lost its jacket many years ago. Hardy's writing is a joy. As the editors say, his enthusiasm stands out. 'It is quite apparent that he is devotedly obsessed by, and interested in animals.' In a chapter on larval forms he introduced me to Walter Garstang's wonderfully comic and informative verses, for example of the larval sea snail he writes: 'The Veliger's a lively tar, the liveliest afloat, A whirling wheel on either side propels his little boat ... .'

It was surely serendipitous that Hardy's research student, Richard Bainbridge, was my lecturer at Cambridge, and then became my Ph.D. supervisor and friend. And perhaps Hardy's chapter on 'Phosphorescence and photophores' was a subliminal spur to my own later research on light in the sea! Either way, his book was truly inspirational.

The End of the Line
by Charles Clover
Ebury Press, 2004



Chosen by Emma Cavan, researcher in marine biogeochemistry and ecosystems

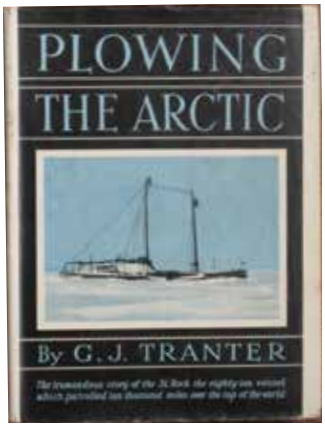
In 2004 when this book was published I was 15. Until that point (and for the subsequent two years) I was focussed on becoming a medical doctor. It was David Attenborough's documentaries, finding *The Good Fish Guide* by the Marine Conservation Society and then this book, *The End of the Line,* that helped me to decide to move from a career in medicine and into the ocean.

The End of the Line (*TEOTL*) was the first non-fiction book I read, and it opened my eyes not only to the problems of wild fisheries, but to the whole world of literature that could teach me things I could not learn in school. After reading *TEOTL* I lectured anyone who would listen to me about the fish we should or should not be eating. I had little success in persuading anyone to change their habits, but reading the book was enough to change mine and to fuel my passion as a marine biologist.

I have not re-read the book in the last 15 years, as the change in society, population and policies mean some of the data have become less relevant. But I find it vaguely depressing that even though we have known for well over a decade that wild fisheries are so damaging, they are still ongoing and people still consume fish without a thought to how that fish was caught or the consequences for ocean life.

For society to change in response to a problem, the problem must impact humans directly. Concern for the well-being of wild turtles in an ocean a person has never visited is not enough to lure them from a Friday-night fish-and-chip dinner (I miss those days – pineapple fritter is not quite the same!). There is some positive change now though. In the last few years the climate crisis and an inceased appreciation of the contribution to the crisis of consuming meat, has created a huge market in 'plant-based' foods. I smile every time I go to the plant-based freezer section in a supermarket and see how it grows in size each year.
To make real change, we just have to find the right argument to pitch, in the hope that we don't reach the end of the line.

Plowing the Arctic
by G.J. Tranter
Hodder and Stoughton, 1944



Chosen by John Phillips, marine bibliophile

For centuries Europeans struggled to find a shortcut to the Far East by sailing westward from the Atlantic to the Pacific through the maze of barren islands that choke the icy waters north of the American continent – the infamous 'Northwest Passage'. After the loss of many ships and not a few fatalities the route's feasibility was eventually proved in 1903–06 when a Norwegian, Roald Amundsen, and his six companions sailed their sloop *Gjøa* from Qeqertarsuaq in Greenland to Nome in Alaska.

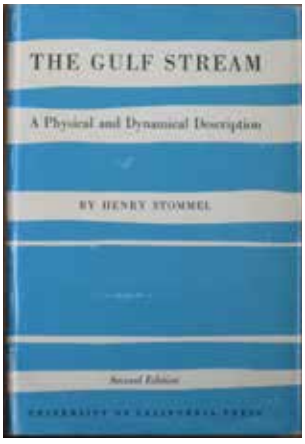
Considering the difficulties they encountered, it's hardly surprising that 36 years elapsed before the next ship passed through those waters – the Royal Canadian Mounted Police schooner *St Roch*, skippered by Sergeant Henry Larsen, another Norwegian by birth, with a crew of seven RCMP constables. Their voyage differed from Amundsen's in some important ways: *St Roch* was larger (32 m) and her auxiliary engine was more powerful (112 kW). She travelled eastward (from Vancouver to Newfoundland) and the journey was completed sooner, in a little over two years (1940–42) instead of three.

But in one respect nothing had changed: the Arctic environment. For about ten months of the year *St Roch* was locked in the ice, where she served as a base for two-man patrols visiting isolated Inuit settlements by dog sled. During the brief season when the sea was at least partly navigable she was in even greater danger from the violent storms, dense fogs, shoal water and, in particular, ice floes driven by the wind and tidal currents. The *St Roch* came close to destruction, as had *Gjøa* in her day.

So why do I recommend a book that describes the *second* transit of the Northwest Passage, the 'runner-up' as it were? My answer is that the motive for this expedition was not just a desire to beat the elements; it was undertaken by a working vessel and her largely untried crew as an extension to their regular task of patrolling Canada's northern territories. Of course Larsen himself was by no means ordinary; he must have possessed the mental strength necessary for any leader who is to succeed in remote and hazardous situations. I read this account of his achievement some fifty years ago, and I remain impressed.

Henry Larsen died in 1964, aged 65. The *St Roch* survives, housed beside the Maritime Museum in Vancouver. I have no doubt that Larsen ran as tidy a ship as circumstances permitted, but I think he would be shocked to see her looking quite so shiny and spotless – and indoors!

The Gulf Stream: A Physical and Dynamical Description
by Henry Stommel
Cambridge University Press, London, 1958



***Chosen by Angela Colling, Editor of* Ocean Challenge**

Until extremely recently, I've never owned a copy of this – for me – very significant book. At university I used a copy obtained on long interlibrary loan by my mum, from Paignton library. Later, when I wanted to use it in connection with teaching, I photocopied an interlibrary loan copy. Opening my newly acquired book a few months ago took me right back to when I first read it.

The Gulf Stream was first published in 1955, in the USA. This was before the time of computer modelling as we know it today – predicted circulations were obtained by solving equations directly and plotting the results (e.g. streamlines or sea-surface height) by hand. Although I know very little about modelling, I can enjoy talks about modelling because reading the book effectively introduced me to some of the principles behind it.

The book begins with a brief history of the understanding of the causes of the Gulf Stream – my first encounter with the history of oceanography, which I've continued to be fascinated by. But perhaps the thing I liked most about the book was the strong relationship between the text and the figures. Possibly influenced by this, I found that, for me, a good way to explain a scientific concept in writing is to find or create a good diagram, and then write with reference to the diagram.

Strangely the book may have helped me get my first job at Cambridge University Press, as at the interview I was asked to name a book that was important to me. I chose *The Gulf Stream*, not knowing that CUP was the publisher in the UK – though they don't seem to have done a very good job at getting the book distributed!

People reading the book today might well not value the same qualities as I did, but it still demonstrates the importance of clear explanations and how communication of science – particularly by writing – is a vital part of doing science; and writing about science can be career in itself. Often, of course, as a teacher and/or writer, it is only by explaining a concept to yourself in writing and/or a diagram, that you can clarify your thoughts sufficiently to explain the idea to others.

If there is a book that has inspired you, or changed the course of your career, please write in and tell us about it in 300–400 words.

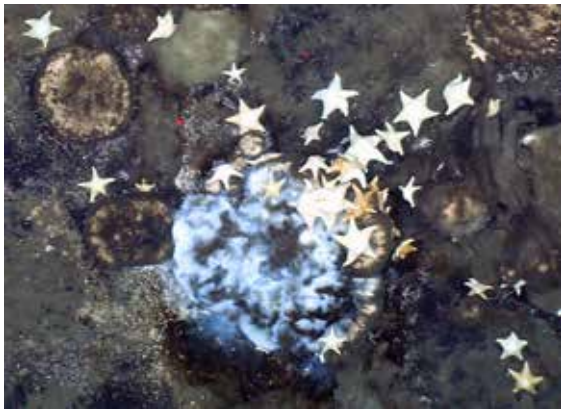
Send your contibutions to AngelaMColling@gmail.com

Giant sponges discovered on Arctic seamounts

The Langseth Ridge – part of the ultra-slow-spreading Gakkel Ridge – lies below the Arctic sea-ice at 87°N (cf. map on p.17). It consists of a chain of three seamounts, and it was on the upper parts of these seamounts that an expedition on RV *Polarstern* found flourishing benthic communities dominated by sponges. The sponge grounds covered a total area of >15 km^2 across the peaks of the seamount chain and the 'saddles' between them, with the densest aggregations and most massive sponges on the flat upper regions of the seamounts, at depths of 721–585 m (Figure 1).

Sponges take in dissolved organic material from seawater, but are primarily filter feeders, so initially it was a mystery how the biomass of sponges on the Langseth Ridge could be comparable to that of shallower sponge grounds. Here, the short spring/summer season and the permanent ice cover means that productivity of ice algae and pelagic plankton is low, with the result that organic detritus from above provides less than 1% of the sponges' carbon demand.

To investigate these intriguing sponges researchers on the *Polarstern* expedition investigated the sponge beds using under-ice sea-floor mapping, along with biomass sampling and analysis. The results were published in *Nature Communications* (see Further Reading).



Upper *A sponge colony with older individuals producing juvenile sponges by budding. This colony sits on the basaltic slope of a seamount, with a thin cover of sediment.* ***Lower*** *A dense assemblage of sponges; in the centre, a dying sponge, covered by a bacterial mat, has attracted predatory starfish.*

(The photos each show an area of around 2 m by 4 m and were taken using the Alfred Wegener Institute's PS101 AWI OFOS system)

There bulk of the sponge biomass is made up of *Geodia parva*, *G. hentscheli* and *Stelletta rhaphidiophora*, all of which (like many other sponges) host a symbiotic community of bacteria which contribute to the health of the sponges by transferring nutrients, disposing of the sponges' metabolic waste and producing antibiotics.* The sponges reproduce by budding (*upper photo*), which means that juvenile sponges are equipped with their microbial symbionts from the beginning.

The fact that these sponges live with symbionts does not explain how they can flourish in such an apparently food-poor environment. To establish what is supporting the sponges, the researchers collected samples of sponge tissue and analysed fatty acid compositions, and stable carbon and nitrogen isotope compositions, for comparison with possible food sources.

Carbon dating showed that the large sponges were very old: tissue age increased with radial distance from the centre, and indicated a growth rate of 0.55 mm yr^{-1}, meaning that adult sponges were typically around 300 years old. The juvenile spnges (1–5 cm diameter) collected were mostly ~ 133 years old.

Living on an extinct ecosystem

In the densely populated upper parts of the seamounts, the sponges were underlain by a mat of siliceous spicules (components of the sponges' internal skeleton), often intermixed with empty worm tubes and bivalve shells. The worm tubes most frequently observed within this mat were identified as those of *Polybrachia*, the spectacular giant tubeworms with red feathery 'gills' extending from white chitin and proteinaceous tubes, associated with hydrothermal vents and seeps.

Carbon dating of material collected from the underlying mats of worm tubes and bryozoans indicated that the hydrothermal community on the seamount chain was active ~ 2400 years before the sponges colonised the area. The radiocarbon age of sediment samples collected from beneath the spicule–tube mat was found to be even older, by >1400 years. The oldest material from the hydrothermal community were bivalve shells (~ 7162 years).

Analysis of the sponge tissue suggested that much of the carbon incorporated into the sponges was in dissolved form, probably obtained via their symbionts. It is likely that the remains of the *Polybrachia* tubes play an important role in the sponges' nutrition: the stable carbon and nitrogen isotope compositions of the sampled sponge tissue were closest to those of the *Polybrachia* tubes, and the microbes in the sponge holobiont have the genes to digest refractory (hard to break down) particulate as well as dissolved organic matter.

The scientists also showed that the sponges act as ecosystem engineers: they can move over the spicule–tube mat, and as they do so they deposit more spicules, adding to the mat and encouraging the settling and trapping of biogenic detritus, which the sponge holobionts can access.

A transient but species-rich ecosystem

The sponge field is rich in species, including glass sponges, shrimps, soft corals and fish and, in addition to the sponges discussed above, a new genus and species of sponge that has been named *Sarsinella karasikensis.* This sponge field as it is today is a transient ecosystem because it depends on a finite resource, and will eventually change anyway as sea-ice cover decreases. The difficulties associated with observing and sampling beneath the ice mean that the deep Arctic Ocean remains understudied, but in this research, close cooperation of scientists from different institutions, in Germany, Norway and the Netherlands, enabled a comprehensive understanding of this surprising hotspot of life.

Ed.

*An ecological unit consisting of a host sponge and microbiome is known as a sponge holobiont. For more about how holobionts function and the techniques used to study them, see the following article.

Further reading

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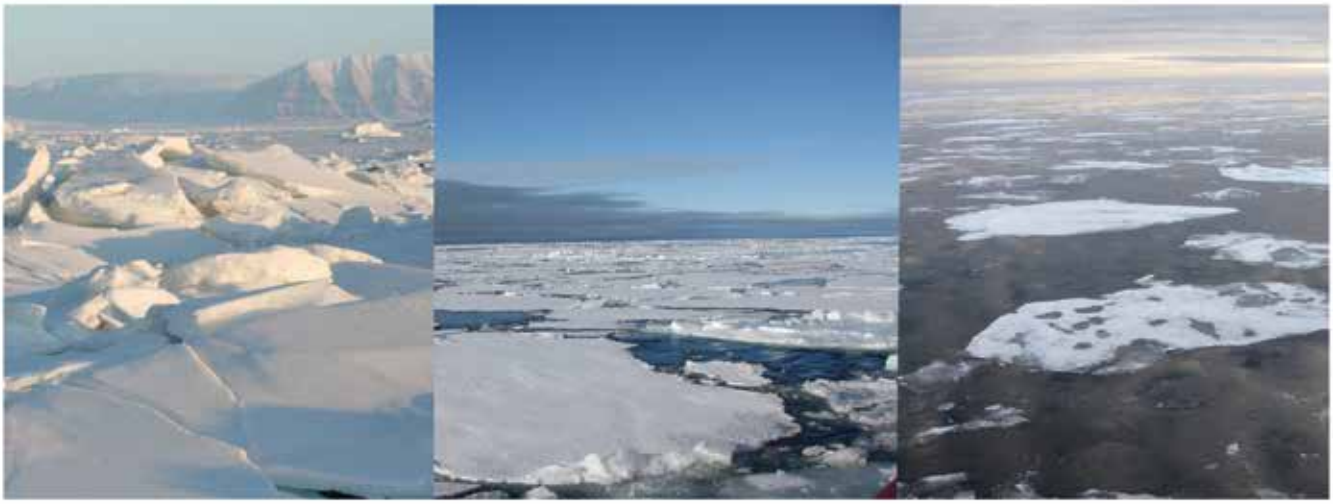
Atlantification of the Arctic



Tom Rippeth

The Arctic Ocean may be the planet's smallest ocean – its surface area is only 4.3% of the total for the global ocean – and it is situated many miles from the heavily populated mid latitudes of the Northern Hemisphere, but over the past decade and a half it has become a focus of interest on account of its rapidly changing climate. Air temperatures in the Arctic are increasing at twice the rate of the rest of the planet through a phenomenon known as Arctic amplification. Consequences include unprecedented heatwaves and wildfires over northern Europe and Siberia, declining sea-ice cover in the summer facilitating the opening up of new shipping routes, and the potential for new opportunities for hydrocarbon extraction across the far north. It is also possible that Arctic warming could affect weather in mid latitudes.

The Arctic Ocean's abyssal depths (Figure 1) are surrounded by shallow continental shelf seas, which occupy over 40% of its total area. Its main link to the global ocean system is to the Atlantic Ocean via the Fram Strait and the Barents Sea, with limited connections through the Canadian Arctic Archipelago, whilst the shallow Bering Strait provides a link to the Pacific Ocean. In oceanographic terms the Arctic Ocean is in some respects unique: the upper ocean density structure is dominated by changes in salinity (which increases with depth), and the ocean as a whole is relatively fresh compared with the other oceans because of the large river inflows. It also has very low levels of mixing in comparison with the oceans further to the south, not least because sea ice isolates the surface ocean from the turbulent atmosphere above.

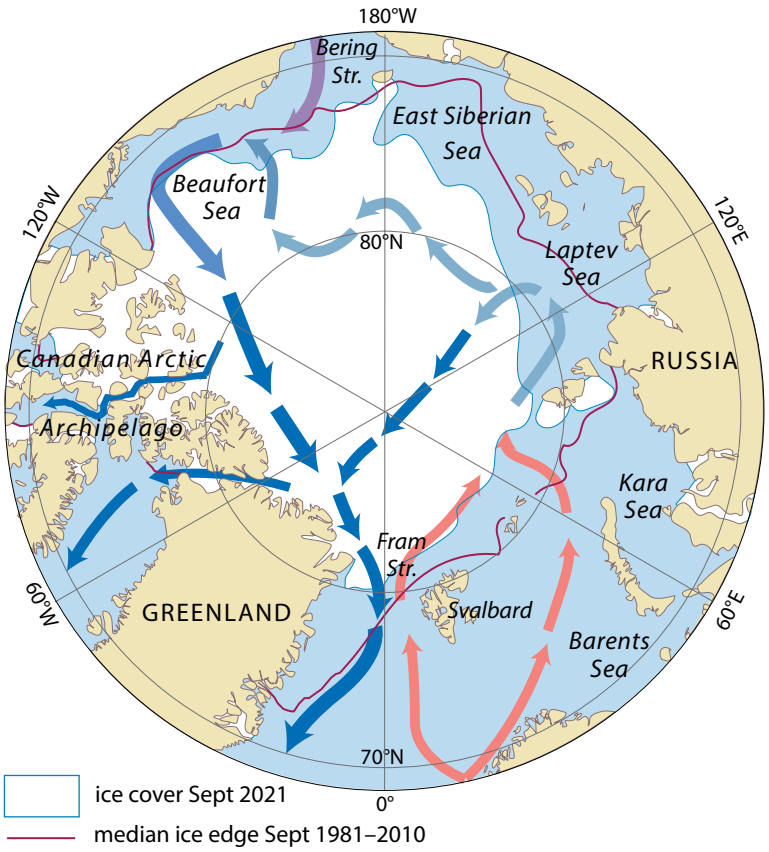


Figure 1 *A map of the Arctic Ocean showing the locations referred to in the text together with the pathway of Atlantic water (red arrows) which enters via the Fram Strait and the Barents Sea; the change in colour from red to blue indicates the transformation of the Atlantic water as it is cooled and freshened as it flows around of the Arctic Ocean. Increasing widths of the current arrows indicate entrainment of Arctic water. Cooler, fresher Pacific water (mauve arrow) flows in via the much shallower Bering Strait.*
(From Lenn, 2009)

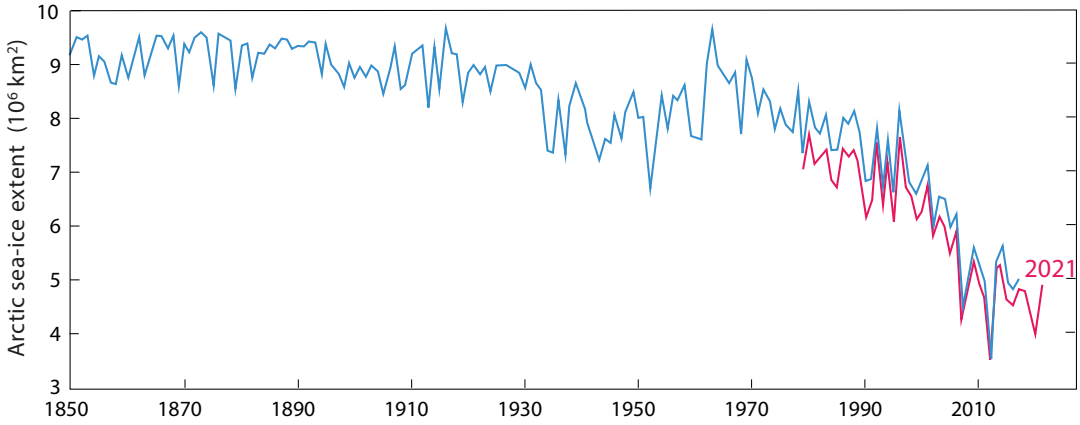


Figure 2 ***Blue plot*** *The variation in the average Arctic sea-ice extent for September (the annual sea-ice minimum area) since 1850, as estimated by Walsh* et al. *(2019) (see Further Reading).* ***Red plot*** *The variation recorded by satellite, from 1979 to 2021. (By courtesy of the National Snow and Ice Data Centre) (Combined plot based on a graphic by Zack Labe)*

Arctic sea-ice extent follows a strong seasonal cycle in response to the extreme seasonal cooling and heating cycle. In the cold of the perpetual darkness of winter, seasonal sea ice grows to cover much of the Arctic Ocean, and it then shrinks back in the 'midnight sun' of summer, reaching its minimum extent every September. The ice that survives the summer, referred to as multi-year ice, gradually gets thicker as a result of ridging and rafting, and seawater freezing on its underside. A conspicuous consequence of the warming of the Arctic in recent decades has been a decline in the extent of sea ice in the summer (Figures 1 and 2). Because less ice is surviving from year to year, the old multi-year ice is gradually being replaced by thinner seasonal ice.

Figure 2 shows how the September (i.e. seasonal minimum) sea-ice extent has changed since 1850. Satellite records over the past 42 years (red plot) have revealed an overall decline in the seasonal sea-ice minimum; it currently decreases by an average of 83 700 km^2 per year, which means that each year sea-ice coverage in September is on average smaller than the year before by an area equivalent to four times the size of Wales. This equates to a rate of loss of sea-ice coverage of 13.1% per decade, relative to the 1981 to 2010 average (National Snow and Ice Data Centre, 2021).

In September 2007 a new record was set with a particularly dramatic reduction in the area of summer sea-ice which hit the headlines globally. The *Independent* newspaper declared: 'Meltdown: Massive loss of Arctic ice means global warming now past point of no return', and there was much speculation in both the scientific community and the media as to whether the dramatic decline was due to a 'perfect storm' of environmental conditions, or to the system reaching a tipping point. Moreover, the seasonal minimum sea-ice extents for the subsequent 15 years were the lowest 15 on record.

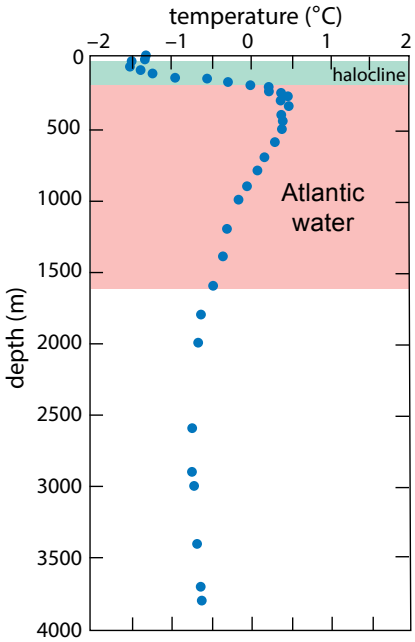
The declining summer sea-ice extent is thought to be a major contributor to Arctic amplification of global warming through an ice–ocean albedo feedback mechanism. The declining sea-ice coverage is facilitating increased ocean warming because dark open water (low albedo) is replacing highly reflective (high albedo) snow and ice, resulting in further ice retreat. This mechanism leads to increased open water areas in summer, with the warmer surface ocean leading to a later return of sea ice, impacting on both the thickness and extent of winter sea ice.

Whilst this feedback mechanism is forced by atmospheric warming, over the past decade or so interest has started to focus on the potential of the intruding warm Atlantic water to impact sea-ice thickness. The Atlantic water flows into the Arctic Ocean through Fram Strait and the Barents Sea as shown in Figure 1. This warm current was first observed by the Arctic explorer and oceanographer Fridtjof Nansen during the 1893–96 *Fram* expedition. He reported the observation in his record of the expedition, *Farthest North*:

> *'The hydrographic observations made during the expedition furnished some surprising data. Thus, for instance, it was customary to look upon the polar basin as being filled with cold water, the temperature of which stood somewhere about –1.5 °C. Consequently our observations showing that under the cold surface there was warmer water, sometimes a temperature as high as +1 °C, were surprising. Again this water was more briny than the water of the polar basin has been assumed to be. This warmer and more strongly saline water must clearly originate from the warmer current of the Atlantic Ocean (the Gulf Stream), flowing in the north and north-easterly direction off Novaya Zemlya and along the west coast of Spitzbergen, then diving under the colder, but lighter and less briny, water of the Polar Sea, and filling up the depths of the basin.'*

A profile of temperature taken by Nansen and his team is shown in Figure 3 (p. 19). The profile illustrates the laborious nature of the measurements made at that time, with 34 discrete water bottle samples, which took four days to collect. The profile was made in a water depth of 3850 m, north of the Laptev Sea (cf. Figure 1) and revealed the layer of intruding Atlantic water extending down to 1600 m, below a colder, fresher halocline layer.

Figure 3 *Profile of seawater temperature reported by Nansen (1897). It was taken over 4 days during 13–17 August 1894 at 81°5' N, 127°28'E through sea ice of thickness 3.17 m. The surface mixed layer below the ice is white. The region of the water column occupied by the halocline, in which salinity increases with depth, is shown in aqua, and that occupied by warmer, more saline Atlantic water is shown in pink.*



It is estimated that the heat associated with the intruding Atlantic water is sufficient to melt the sea ice covering the Arctic Ocean several times over. However, mixing across the halocline layer is weak, so it acts as a barrier to significant heat fluxes. Later high-resolution profile measurements revealed that across much of the Arctic the temperature and salinity structure across the lower halocline/uppermost Atlantic water shows sharp changes in temperature and salinity occurring every few metres depth. This is a consequence of the development of double diffusive convection leading to the formation of stepped temperature and salinity profiles or 'staircases' (see Lenn (2009) in Further Reading, and Figure 6 overleaf). These features are associated with cooler, less saline water overlying warmer, more saline water and can only exist in regions with low levels of turbulence. Furthermore, their presence implies only a weak leakage of heat from the Atlantic water towards the surface (< 1 W m^{-2}). A notable exception to this situation is the shelf-break region to the north of the Barents Sea and Svalbard, where strong tidal mixing prevents the formation of double diffusive convective staircases and greatly weakens the halocline barrier, leading to upward heat fluxes as large as 50 W m^{-2}.

Atlantification

In recent years there has been growing evidence of the increasing impact of heat associated with the inflowing Atlantic water in melting sea ice from below and preventing its regrowth in winter. Warming of the inflowing Atlantic water by ~ 1 °C around 2005 has resulted in a retreat of winter sea ice out of the southern Barents Sea, with the southerly extent of the winter sea-ice coverage restricted to around 76° N, as shown in Figure 4.

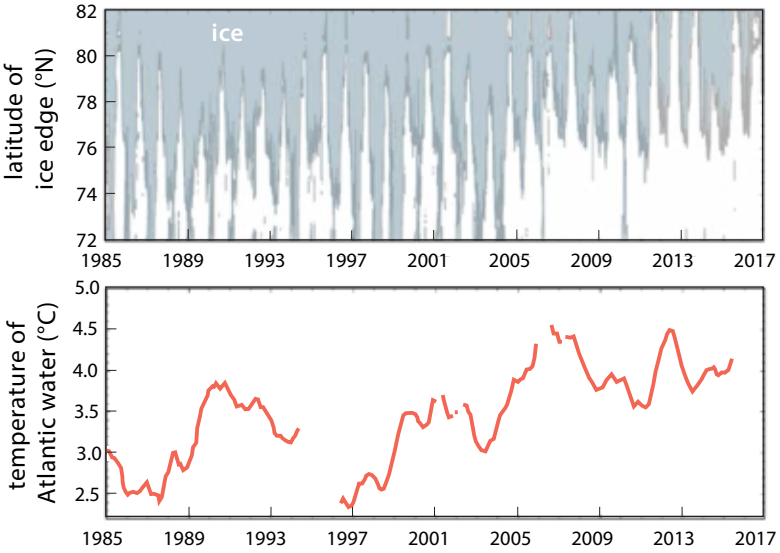


Figure 4 Upper *Variation in the latitudinal extent of sea ice in the Barents Sea between 1985 and 2017, together with* ***(lower)*** *the corresponding temperature of inflowing Atlantic water. (Redrawn from Barton* et al. *(2018) in Further Reading)*

Further to the east, annual CTD surveys to the north of the Laptev Sea, around the 125°E meridian, by the NABOS team led by Igor Polyakov at the University of Alaska, have revealed a warming and a shoaling of the Atlantic water coupled with a weakening of the halocline stratification in recent years. For example, a CTD profile taken in a water depth of 4000 m on 1 September 2018, approximately 40 km to the west of that reported by Nansen (Figure 5), shows that the Atlantic water temperature maximum has increased by over a degree, to > 1.5 °C, and occurs at a shallower depth, in comparison with that reported by Nansen.

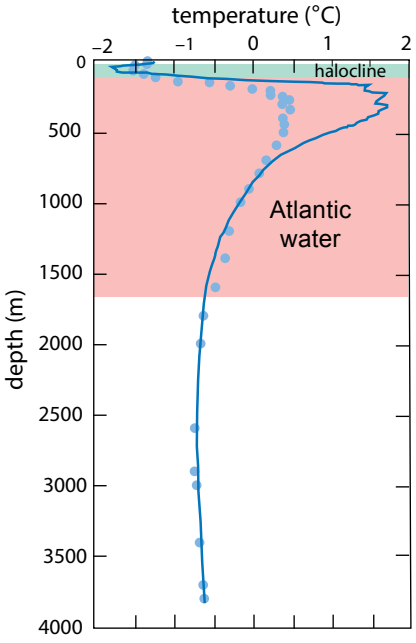


Figure 5 *Temperature profile taken in Sept. 2018, about 40 km to the west of that reported by Nansen, shown alongside in pale blue. Note that in 2018 Atlantic water was found at a shallower depth, below a thinner halocline layer, and its maximum temperature had increased from 0.4 °C to >1.5 °C.*

Further, the upward oceanic heat flux associated with the Atlantic water is estimated to have increased from 3–4 W m^{-2} (2007–2008) to >10 W m^{-2} (2016–2018). As a result, over that time, the thickness of sea ice formed in winter in that region has decreased by more than half. Furthermore, mooring observations in the upper 50 m of the water column indicate that current speeds and associated shear have increased over this period, pointing to greater coupling between wind, sea ice and the upper ocean. The coincidence of the increasing upper ocean currents and weakening stratification suggests more turbulent mixing and a new positive feedback mechanism in which reduced sea-ice extent facilitates more energetic inertial currents, leading to enhanced mixing up of Atlantic water heat towards the surface, melting back ice further.

The changes documented in the eastern Arctic Ocean are summarised in Figure 6; today there is more open water, and thinner and more mobile ice, leading to increased wind-driven currents, which in turn drive turbulent mixing, which replaces the double diffusive fluxes. This, together with a resultant warming of the surface mixed layer, a weakening of halocline stratification, and a warming and shoaling of the Atlantic water, are resulting in increased Atlantic water heat fluxes. The net result could ultimately be a shift in ocean state in this region, towards that found further to the west, where strong turbulent mixing dominates the ventilation of the Atlantic water which in turn greatly restricts or prevents sea-ice growth. The changes in the eastern Arctic also highlight the key role of lower latitude processes (which set the temperature of the inflowing Atlantic water) in determining the future evolution of the Arctic Ocean.

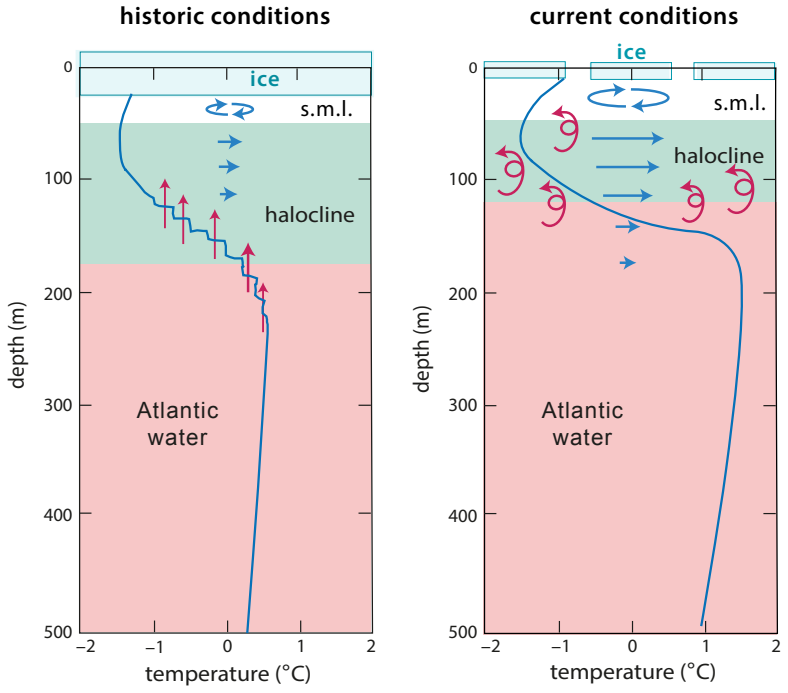


Figure 6 *Schematic diagrams of the uppermost 500 m in the eastern Arctic Ocean demonstrating the shift in recent years. Prevously, ice cover was extensive, the halocline layer was thicker, upward movement of heat was limited and was associated with thermohaline 'staircases' across the boundary between the halocline layer and the Atlantic water. Today the ice is thinner and more mobile, and there are stronger inertial currents in a warmer surface mixed layer (s.m.l.) with a thinner halocline, together with warming and shoaling of the Atlantic water and increased vertical mixing caused by stronger wind-driven currents, all conspiring to increase upward heat fluxes from the Atlantic water layer. (Redrawn from Polyakov* et al.*, 2020, in Further Reading)*

These new insights into the changing Arctic Ocean further highlight the complex relationship between stratification and mixing in the Arctic Ocean, where small perturbations in heat fluxes determine whether or not sea ice is able to form. The processes determining the water properties on the wide expanse of continental shelves around the Arctic Ocean are key to setting halocline stratification and yet are potentially most affected by sea-ice retreat. The high latitude, and hence marked Coriolis effect, imposes dynamical constrains on the rate of conversion of tidal energy to mixing, and also on the propagation of wind energy into the ocean through the generation of inertial waves. Identification of the energy pathways from both tides and the wind through the Arctic Ocean is therefore vital to the accurate parameterisation of the oceanic mixing processes which ventilate the Atlantic water.

The past decade or so has seen the increasing influence on Arctic sea ice of heat exported from the Atlantic Ocean into the Arctic Ocean. Within the eastern Arctic increased melting has triggered a new feedback mechanism whereby decreasing sea-ice extent is allowing an increased coupling between the atmosphere and ocean, which in turn is resulting in more relatively warm Atlantic water being stirred up towards the surface, reducing sea-ice extent further. The pernicious influence of the Atlantic water in this region is leading to a change in water column structure which could be viewed as a tipping point.

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Acknowledgement

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Tom Rippeth is the established Chair of Physical Oceanography at the Bangor University School of Ocean Sciences. He is an observational oceanographer who specialises in using measurements of turbulence in the ocean to identify the key processes driving oceanic mixing. His interest in the Arctic was initially encouraged by Sheldon Bacon and the late Seymore Laxon through involvement in the International Polar Year Arctic Synoptic Basin-wide Oceanography programme. t.p.rippeth@bangor.ac.uk

Fish can modify ecosystems too

An article in the last *Ocean Challenge* described how whales may engineer their ecosystem by using their huge bulk to mix the upper ocean. A recent study led by researchers from the University of Southampton has shown that fish may do something similar, though on smaller length scales.

The researchers were working in an area of upwelling off the north-west coast of the Iberian Peninsula, and were intending to study how vertical mixing affects marine life, using a microstructure profiler, which measures variations in current speed and temperature over vertical distances as small as a millimetre. Measurements were taken for two weeks, 24 hours a day.

It was a surprise when at night the microstructure profiler showed that in an area close to the vessel there was a 10–100-fold increase in turbulence and mixing similar to what might be caused by a major storm, although the weather was calm.

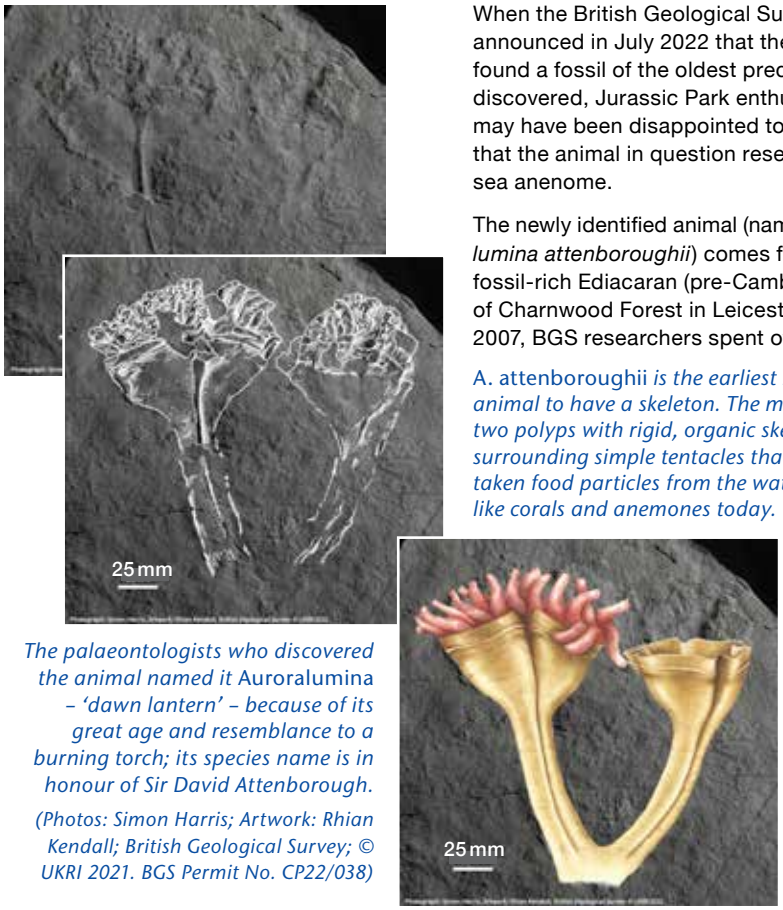
Further investigations, including studying signals from the ship's echo-sounder and deploying small fishing nets to sample the water, revealed the answer. The nets came up full of recently spawned eggs of the European anchovy, *Engraulis encrascicolus* – it was the energetic behaviour of large numbers of anchovies coming together for night-time spawning that was causing the turbulence.

It had previously been thought that only turbulence and mixing caused by tides and waves would be significant in the ocean; it was assumed that turbulence caused by fish would produce minimal mixing because the eddies that fish generate while swimming are too small. While true in the open ocean, where seawater properties are more homogeneous, closer to land, where waters are more stratified, mixing by fish could be important in redistributing seawater constituents, e.g. stirring up nutrients, so promoting phytoplankton growth, and reoxygenating layers that had become depleted in oxygen.

Ed.

This study formed part of the REMEDIOS project and the results are described in Fernández Castro, B., *et al.* (2022) Intense upper ocean mixing due to large aggregations of spawning fish. *Nature Geoscience* **15**, 287–92. doi: 10.1038/s41561-022-00916-3

Much more exciting than another dinosaur …



The palaeontologists who discovered the animal named it Auroralumina *– 'dawn lantern' – because of its great age and resemblance to a burning torch; its species name is in honour of Sir David Attenborough.*

(Photos: Simon Harris; Artwork: Rhian Kendall; British Geological Survey; © UKRI 2021. BGS Permit No. CP22/038)

When the British Geological Survey (BGS) announced in July 2022 that they had found a fossil of the oldest predator yet discovered, Jurassic Park enthusiasts may have been disappointed to discover that the animal in question resembles a sea anenome.

The newly identified animal (named *Auroralumina attenboroughii*) comes from the fossil-rich Ediacaran (pre-Cambrian) beds of Charnwood Forest in Leicestershire. In 2007, BGS researchers spent over a week cleaning a 100 m^2 rock surface with toothbrushes and pressure jets. They then took a rubber mould of the whole surface, and amongst the impressions of over 1000 fossils found one that didn't seem to fit.

A. attenboroughii is the earliest known animal to have a skeleton. The mould shows two polyps with rigid, organic skeletons surrounding simple tentacles that would have taken food particles from the water column, like corals and anemones today.

Dating using zirons in the surrounding rocks gave the animal an age of ~560 Ma, confirming that it lived during the Ediacaran Period, a time when – it was thought – all animals had simple body plans unlike those of most modern animals. The 'Cambrian Explosion', a period of diversification which began ~20 million years later, is known to be when the body plans of most living phyla evolved. However, *Auroralumina's* complex body plan displays some characteristics similar to those of early medusozoans (jellyfish) and others more typical of anthozoans (sea anemones).

The ancient rocks in Charnwood closely resemble sediments deposited on the flanks of volcanic islands/seamounts. With the exception of *A. attenboroughii*, all of the fossil animals on the cleaned rock surface were anchored to the sea floor and had been knocked over in the same direction by a deluge of volcanic ash sweeping down from above. *A. attenboroughii* lies at an odd angle and has been detatched from its base, so appears to have been swept down from above.

Ed.

See Dunn, F.S. *et al.* (2022) A crown-group cnidarian from the Ediacaran of Charnwood Forest, UK. *Nature Ecology & Evolution* doi: 10.1038/s41559-022-01807-x

Why sunscreen is bad for corals

It's been known for a while that oxybenzone, a UVA and UVB blocker and a common active ingredient in sunscreens, can damage coral reefs, and some countries and US states have banned swimmers from using sunscreens that contain it.*

Now a group of scientists led by William Mitch at Stanford University has discovered why oxybenzene is toxic to corals and other cnidarians. The group studied the effects of oxybenzone exposure on sea anemones and a mushroom coral in tanks of simulated seawater. Each day, oxybenzone was added to the tank to produce levels close to those found in some reef zones. After 17 days, all of the sea anemones were dead.

Oxybenzone works by absorbing UV light, then releasing the energy as heat. The researchers found that once it is metabolised, oxybenzone is modified by attachment of glucose; the resulting compound can still absorb light, but now does not have a way to release the energy as heat. Instead, it forms reactive oxygen species which cause damage to tissue.

It was also found that the algal symbionts of anemones and corals concentrate the altered oxybenzone. This seems to provide some protection to their hosts as bleached anemones, with no symbiotic algae, are more susceptible to damage when exposed to ultraviolet light and oxybenzone. This is a worrying discovery when, in a warming ocean, symbiotic algae are increasingly deserting their hosts.

14 000 tonnes of sunscreen enters the ocean each year, and ironically some will come from ecotourists and others who care about coral reefs.

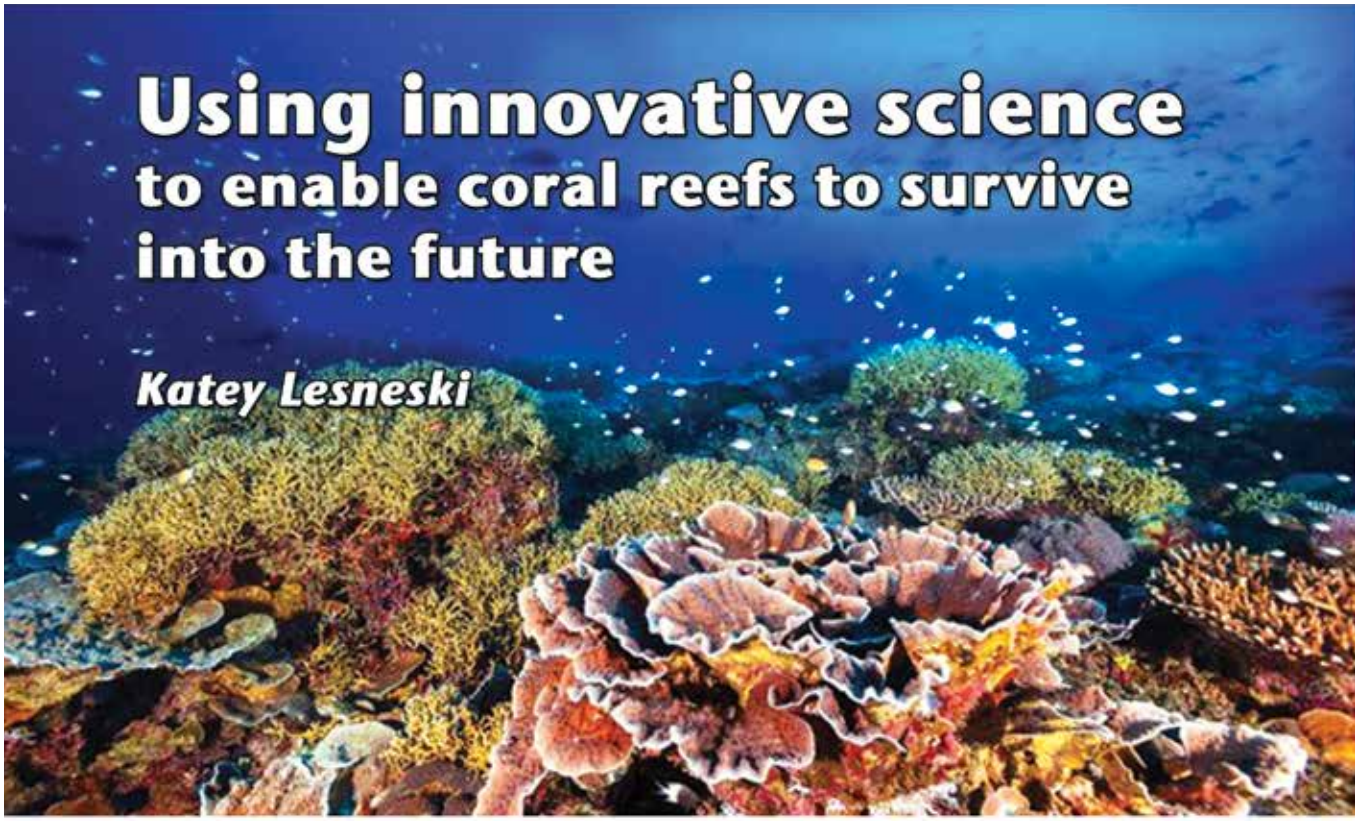
*At the time of writing, many major UK retailers are stocking sunscreen containing oxybenzone (and another possibly damaging chemical, octinoxate).

See Vuckovic *et al.* (2022) *Science* **376** (6593), 644–8. doi: 10.1126/science.abn2600

A ray of hope for struggling corals

In the following article Katey Lesneski, Director of Restoration Science at Coral Vita in Freeport, Grand Bahama, describes some exciting work which uses cutting-edge methods developed at marine institutes around the world to enable corals to grow up to 50 times faster than they would in nature while boosting their resilience to climate change, so restoring reefs in the most effective way possible.

For more information, and to learn how to adopt a coral, go to https://www.coralvita.co



Katey Lesneski is a key member of Coral Vita, based on Grand Bahama. Coral Vita won the Royal Foundation's prestigious 'Revive Our Oceans' Earth Shot Prize in 2021

Coral reefs are amongst the most biodiverse ecosystems on Earth, with up to 25% of all marine species depending on reefs at some point during their life cycle. This wonderful array of species and the framework of reefs themselves are not only valued for their intrinsic beauty, but provide myriad economic and ecological benefits across the globe's tropics. The total monetary value of coral reefs can be difficult to estimate, but the upper limit is assessed at around $11 trillion. Accounted for in this value are billions of dollars spent annually by tourists, jobs associated with reefs, commercial and sustenance fisheries, shoreline protection by way of reducing erosion and flooding during storms, current and potential drug compound discovery, and connection to and buffering of other important ecosystems such as seagrass beds and mangroves. Despite their clear importance for the over half-billion people who depend on these ecosystems daily, coral reefs face a number of threats across varied geographic scales. However, as we are discovering more about the complexity of coral-reef systems, we are learning innovative ways to protect and restore reefs using new scientific knowledge and techniques.

The title image of a coral reef off Mayotte Island in the Mozambique Channel is by courtesy of Gaby Barathieu and the Ocean Image Bank

Threats to reefs

At the smallest scale, reefs can be physically damaged by careless divers or boaters, who can destroy decades of growth in an instant. Shoreline development and projects that involve dredging near coasts both lead to physical damage of reefs, increased sedimentation and degraded water quality, and show no sign of slowing as the world's population continues to increase. Pollution discharged from land, ranging from sewage to fertilisers, can affect reef systems when runoff is uncontrolled and untreated. Thinking regionally, overfishing and specifically the extraction of herbivorous fish, coupled with the loss of other herbivores such as sea urchins, have led to an increase in macroalgae – seaweeds – strong spatial competitors for reef substrate that can also overgrow and effectively smother corals.

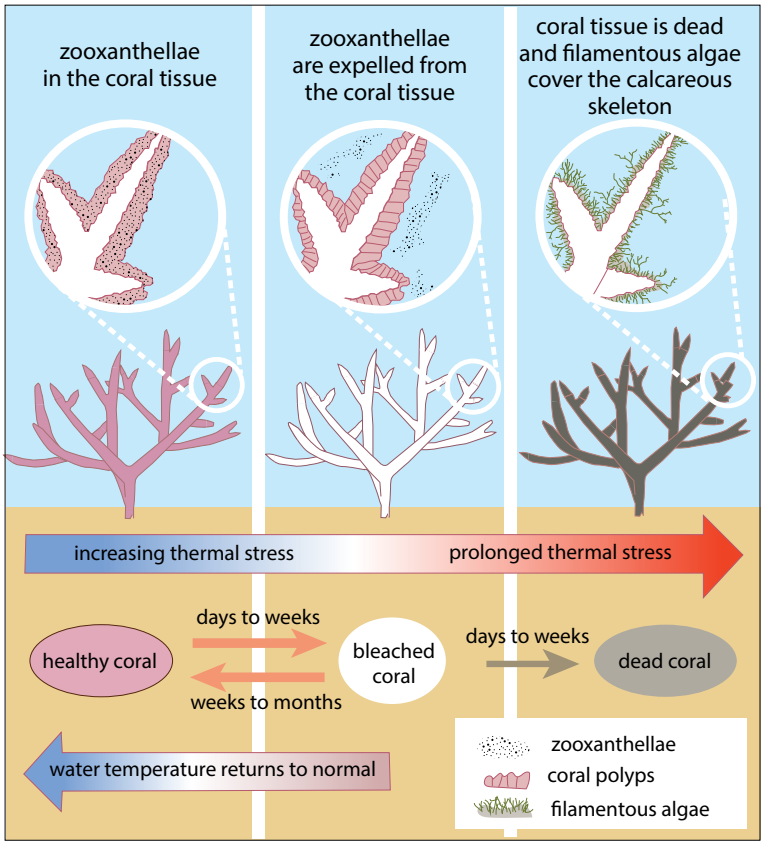
While all of these threats can be locally or regionally targeted for remediation, corals also face perhaps the most daunting stressor – the effects of global climate change. With documented rises in sea-surface temperature throughout the 20th century and an increase in ocean acidity, corals have already been subjected to declining environmental conditions. These conditions are forecast to worsen considerably in the coming decades, leading to increased frequency, intensity and duration of large-scale bleaching events which can cause high levels of mortality across hundreds of square kilometres of reef. Thus stakeholders involved in decisions concerning reef management, conservation and restoration constantly have to consider the compounded effects of these global stressors, even if aggressive intervention is already being undertaken at local and regional scales.

Scientists are striving to understand in more detail the impact of these effects on corals and the many reef biota that constitute coral reefs – and not just from an ecosystem perspective. Surprisingly, not all corals are declining and some are even thriving. Thanks to recent advances in applications of genetic sequencing coupled with decreasing costs, researchers are able to examine many facets of genetic diversity and variation within and between corals and their closely associated microorganisms, providing preliminary explanations as to why some coral populations persist and thrive today, and providing a roadmap for future action, including expanding and improving coral-reef restoration efforts.

The coral holobiont

Reef-building corals (scleractinians) are cnidarians (related to sea anemones and jellyfish) that form colonies of genetically identical polyps (clones) and produce limestone skeletons with the assistance of symbiotic single-celled dinoflagellate algae known as zooxanthellae. Much work has been done to understand the tightly coupled mutually beneficial relationship between the coral host and these zooxanthellae, affectionately referred to by coral scientists as 'zoox'. In exchange for a habitable environment in the coral tissue along with a supply of respiration by-products needed for photosynthesis, the zooxanthellae provide the coral with sugars and amino acids and aid in skeletal growth via calcification. In fact, zooxanthellae may provide over 90% of the energy corals require, and contribute to the wide array of colours corals exhibit. This relationship, while more than 100 million years in the making, is not always stable. During warm-water events such as occur during an El Niño, or under other non-ideal environmental conditions, corals can undergo bleaching, wherein the zooxanthellae either leave or are expelled from the coral host, leaving clear tissue which allows the white skeleton below to be visible (Figure 1). Recent research has revealed that different clades (strains) of symbionts may confer variable benefits including increased heat stress tolerance in the coral host, and following a period of stress (such as undergoing bleaching) some corals may selectively acquire certain clades.

Figure 1 Left *Illustration of the stages of coral bleaching due to thermal stress. (From Lentz (2012), adapted from Marshall and Schuttenberg (2006); see Further Reading)* ***Right*** *Bleached corals overgrown with filamentous algae, photographed off Fiji in 2016. (The Ocean Agency / Ocean Image Bank)*



While the coral–algae relationship was characterised nearly 50 years ago, only over the last 20 years have scientists studying corals come to understand that corals are actually much more complex and host a wide variety of microorganisms; such a multi-species ecological unit is known as a 'holobiont'. Community members found in the mucus that covers the soft tissue, the soft tissue itself, and the skeleton of healthy corals, include bacteria, Archaea, fungi, and even viruses (Figure 2). Recent studies have described a number of hypotheses related to functional and dysfunctional associations among these various inhabitants. For example, metabolic complementation may be a driver of some coral–bacteria and coral–archaea associations that improve nitrogen fixation and cycling, which are important in the characteristically oligotrophic waters of tropical coral reefs. Some fungi assist in nitrogen and carbon cycling, and may provide defence against pathogenic bacteria. Viruses can aid in regulating colonisation of bacterial pathogens, with active bacteriophages in the surface mucous layer. As it is a highly dynamic and open system, the diversity and composition of the holobiont can vary within a species over different time scales, across different reefs and regions, and in response to environmental changes including stressors such as warm-water events.

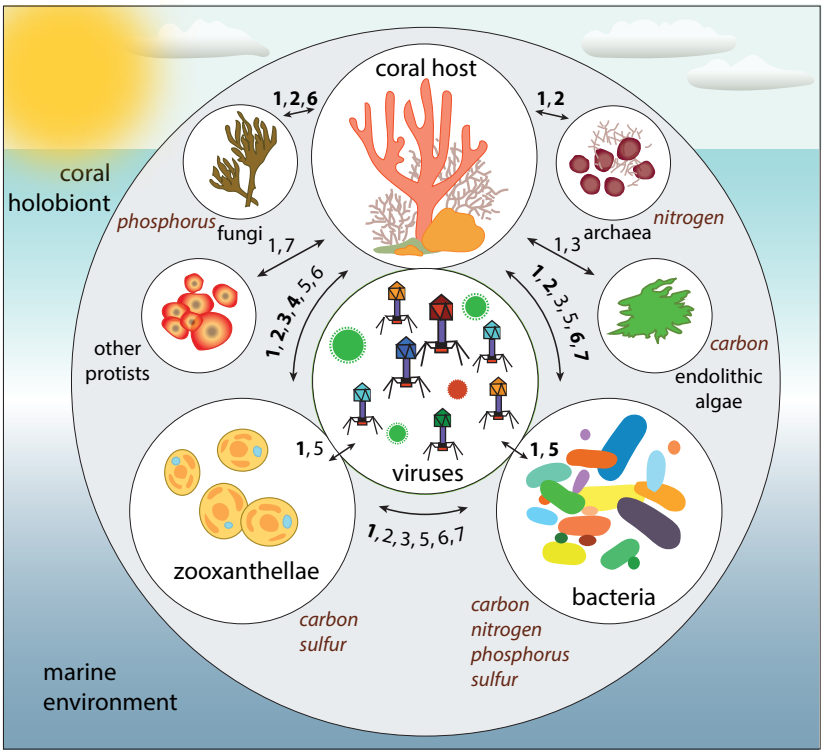


Figure 2 *Diagram of known relationships (bold numbers) and inferred relationships (other numbers) among constituents of the coral holobiont.* ***1*** *Shelter, protection and nutrient transfer;* ***2*** *Nutrient cycling;* ***3*** *Transfer of the products of photosynthesis;* ***4*** *Main organic carbon provision;* ***5*** *Gene transfer, control of microbial populations, microbiome modulation;* ***6*** *Antimicrobial activity;* ***7*** *Nutrient input, pathogen control.*

Chemical elements involved in metabolic cycling and exchanges between holobiont members and the host coral are shown in brown.

Archaea are single-celled organisms originally identified as primitive bacteria.

(From Voolstra et al. *2021; see Further Reading)*

Disease control

The same environmental stresses that cause bleaching due to a loss of the zooxanthellae can lead to a dysbiosis, i.e. a disruption of the equilibrium of the holobiont, which results in alternative microbial states that are detrimental for coral health as a whole. Examples include an increase in virulence of viruses found in normally healthy corals as well as an increase in the relative abundance of parasitic bacteria and fungal pathogens, which have all been linked to a variety of coral diseases. While coral diseases have been documented throughout the world for decades, outbreaks are expected to become more frequent due to declining water quality in the face of continued global climate change.

A relatively new disease – Stony Coral Tissue Loss Disease (SCLTD) (Figure 3(a)) – appeared in Florida in 2014, and has since spread to the wider Caribbean. Affecting dozens of coral species and causing rapid tissue loss and death, this disease has spread throughout the region at an alarming rate, yet the exact cause at the microbial level is still unknown. A number of research groups have been testing direct interventions to combat coral diseases including SCLTD, ranging from dosing corals with various probiotics in controlled aquaria, to applying an antibiotic paste to colonies in the wild (Figure 3(b)). Based on the sum findings of such treatment trials, along with experiments and observations of changes in the microbial composition in healthy and diseased corals under various environmental stressors and conditions, scientists are now moving away from the single pathogen/single disease models for corals. Deciphering coral-reef disease ecology and emergent properties* as soon as possible is critical. Additionally, understanding the mechanisms underpinning shifts in holobiont composition and health following stress and/or treatment is particularly important in the context of coral-reef restoration efforts.

*New properties that are hard to predict as they are a result of complex interactions between individual parts of a larger system, such as the coral holobiont.

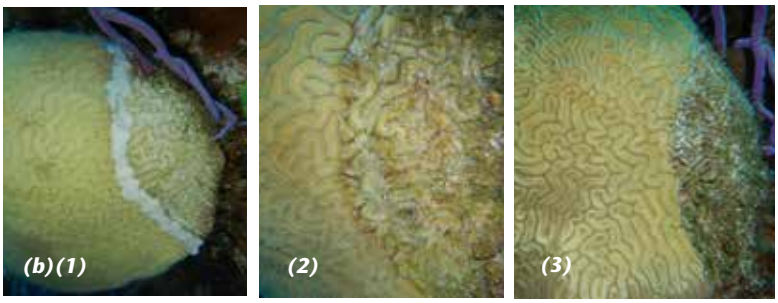


Figure 3 ***(a)*** *A symmetrical brain coral (*Pseudodiploria strigosa*) affected by Stony Coral Tissue Loss Disease. The remaining live coral tissue is on the right-hand side of the coral.* ***(b)*** *Treatment of Stony Coral Tissue Loss Disease on a grooved brain coral (*Diploria labyrinthiformis*) using antibiotics.* ***(1)*** *A lesion on the edge of a colony treated with a white antibiotic paste in March 2020.* ***(2)*** *7+ weeks later, there are some algae on the treatment line, but the disease has stopped progressing.* ***(3)*** *6.5 months later the colony shows no signs of disease progression or reinfection.*
(Photos: (a) Florida Keys National Marine Sanctuary; (b) A. Zimmermann, Turks and Caicos Reef Fund)

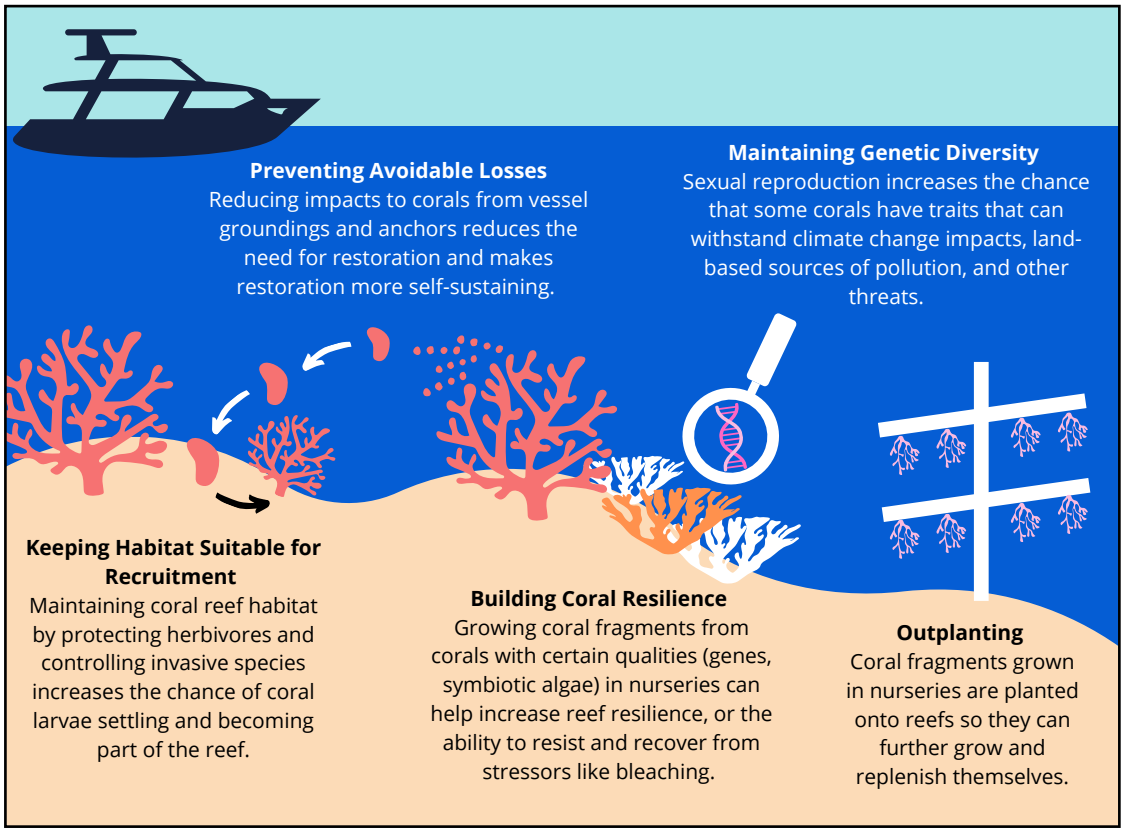


Figure 4 *An overview of approaches to reef restoration, taken from an informatic produced by NOAA's Coral Reef Conservation Program. Of course, addressing the threats from climate change, land-based sources of pollution and overfishing would increase the success of coral restoration.*

Reef restoration

Many countries have been working on reef restoration projects for a decade or more, and have been using various different approaches (Figure 4), but in many circumstances the most appropriate kind of intervention is active restoration. Briefly, corals can be transplanted directly to degraded reef

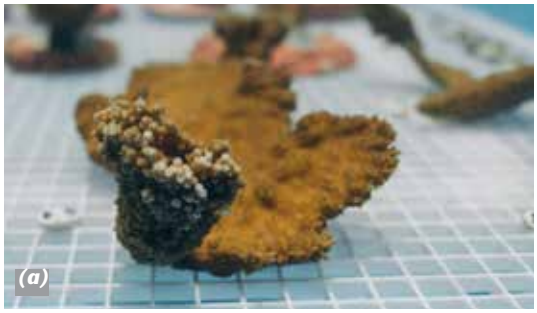


Figure 5 ***(a)*** *A piece of elkhorn coral (*Acropora palmata*) in one of Coral Vita's tanks at Freeport, Grand Bahama. Larger pieces of coral like this are collected from the wild, often as 'fragments of opportunity' (corals that have broken off from a larger colony, e.g. during a storm) that have fallen onto unsuitable substrate such as sand, and would die if left in place. These 'broodstock' colonies can then be cut into microfragments, or 'microfrags'.* ***(b)*** *Microfrags are glued to ceramic plugs and maintained under controlled conditions to maximise their growth and health. Water temperature, light levels, flow and other conditions are monitored constantly and can be adjusted. Counterintuitively, cutting corals into ~1 cm^2 pieces results in faster growth rates as it stimulates a rapid wound healing response. Depending on the species, such corals can grow up to 40 times faster than in the wild.* ***(c)*** *Staghorn coral (*A. cervicornis*) microfragments are returned to a reef offshore Grand Bahama. These individuals all came from the same parent colony (which could regenerate where tissue and skeleton were initially cut) and the microfragments can grow into adult colonies themselves. Planting them close to each other increases the chances that eventually they will fuse their skeleton and tissue together, forming a colony with greater structural strength.* *(See p.29 for a flourishing* Acropora *colony.)* *(Photos: Harry Lee)*

sites from other reefs, or can be 'outplanted' from facilities including land-based aquaria (e.g. Coral Vita's tanks on Grand Bahama; Figure 5) or ocean-based 'nurseries', where corals are maintained, propagated and monitored until they are ready for return to reefs (Figure 4). Goals of such efforts include increasing coral cover, abundance of corals and coral diversity on reefs, with the objective of rebuilding the physical framework and thus the habitat available for other organisms. If successful, other ecological and economic benefits such as providing fish nurseries and protection for coastlines may be enhanced as well.

As all of the steps involved in active restoration can be time-consuming and costly, practitioners and scientists hope that the corals placed onto the reefs will survive long term and eventually will be able to reproduce, sustaining or even growing populations. Thus, in selecting which individual corals to propagate or transplant onto reefs, it is critical to bear in mind the traits that provide an ability to withstand stressful environmental conditions, and those that provide the ability to recover when adverse conditions come to an end. These traits, inclusive of the contribution by all members of the holobiont, can be revealed through various 'omic' approaches, including genomic, transcriptomic, proteomic and metabolomic profiling (Figure 6).

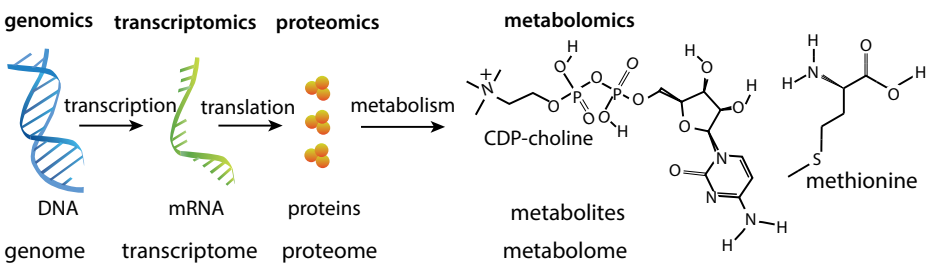
Genetic and molecular approaches

Genomics Sequencing genomes of various corals is often the first step in being able to characterise genetic markers related to responses to various stressors. Such markers may vary within and between coral populations, including populations of the same species, and can be separated into contributions from the coral animal host, the symbiotic algae, and other members of the holobiont. For example, Zachary Fuller at Columbia University led a team to characterise a suite of genetic variants in the coral host and its symbionts associated with both susceptibility to bleaching and tolerance of bleaching, in a key reef-building coral species in Australia. Sequencing of selected colonies can help develop geographic profiles of where individuals with such genetic markers are found, determine which corals to focus efforts on propagating, or even which corals may be suitable candidates for crossbreeding. Genomic studies also allow researchers to characterise genetic diversity within and among populations, which is critical for restoration efforts as more genetically diverse populations have a greater chance of long-term success. Those involved in various steps of reef restoration can track clone lines of different species, and make informed decisions around enhancing genetic diversity on reefs undergoing restoration.

Transcriptomics Transcription is the process that occurs when a gene's DNA sequence is copied in the form of a single strand of RNA, known as messenger RNA or mRNA, which carries the gene's protein information (Figure 6). Analysing the mRNA transcripts produced by the genome at a moment in time allows for a quantitative assessment of gene expression in response to stress. Characterising the levels of up- or downregulated genes (i.e. those whose expression has increased or decreased) across all members of the holobiont, before, during and after stress, can provide insight as to why some corals or coral populations are thriving even during prolonged stress-inducing events, and whether corals are able to shift gene expression in response to such events.

Daniel Barshis and other researchers at Stanford University determined that corals of the same species living in two nearby but very different reef habitats in American Samoa exhibited different levels of expression of genes related to thermal tolerance during normal conditions and while exposed to heat stress during an experiment. Interestingly, corals naturally living in an environment with higher maximum temperatures and greater temperature ranges compared with other habitats exhibited 'frontloading', or a naturally high expression of genes related to thermal tolerance even under normal conditions. These corals are then essentially continuously prepared for heat stress, while counterparts in other environments have to 'turn on' these genes once exposed to it. The corals with higher baseline heat tolerance were also found to harbour more heat-tolerant *Symbiodinium* genotypes, highlighting the need to understand how *all* members of the holobiont may contribute to stress tolerance. Total RNA extraction and sequencing of coral tissue and mucus samples can be used to characterise how various components of the holobiont alter gene expression following natural and

Figure 6 *Hierarchy of the 'omics', the characterisation and quantification of pools of biological molecules that translate into the structure, function and dynamics of an organism. If a gene is upregulated or downregulated, its increased or decreased expression results in an increase or decrease in production of cellular components such as protein. (From Frueh and Burczynski 2021; see Further Reading)*



The coral metabolite CDP-choline is a key chemical involved in phospholipid metabolism, cell signalling and glutamate transport, and is an intermediate in betaine synthesis; methionine is involved in scavenging reactive oxygen species which can cause cellular damage, and its production often increases during heat stress.

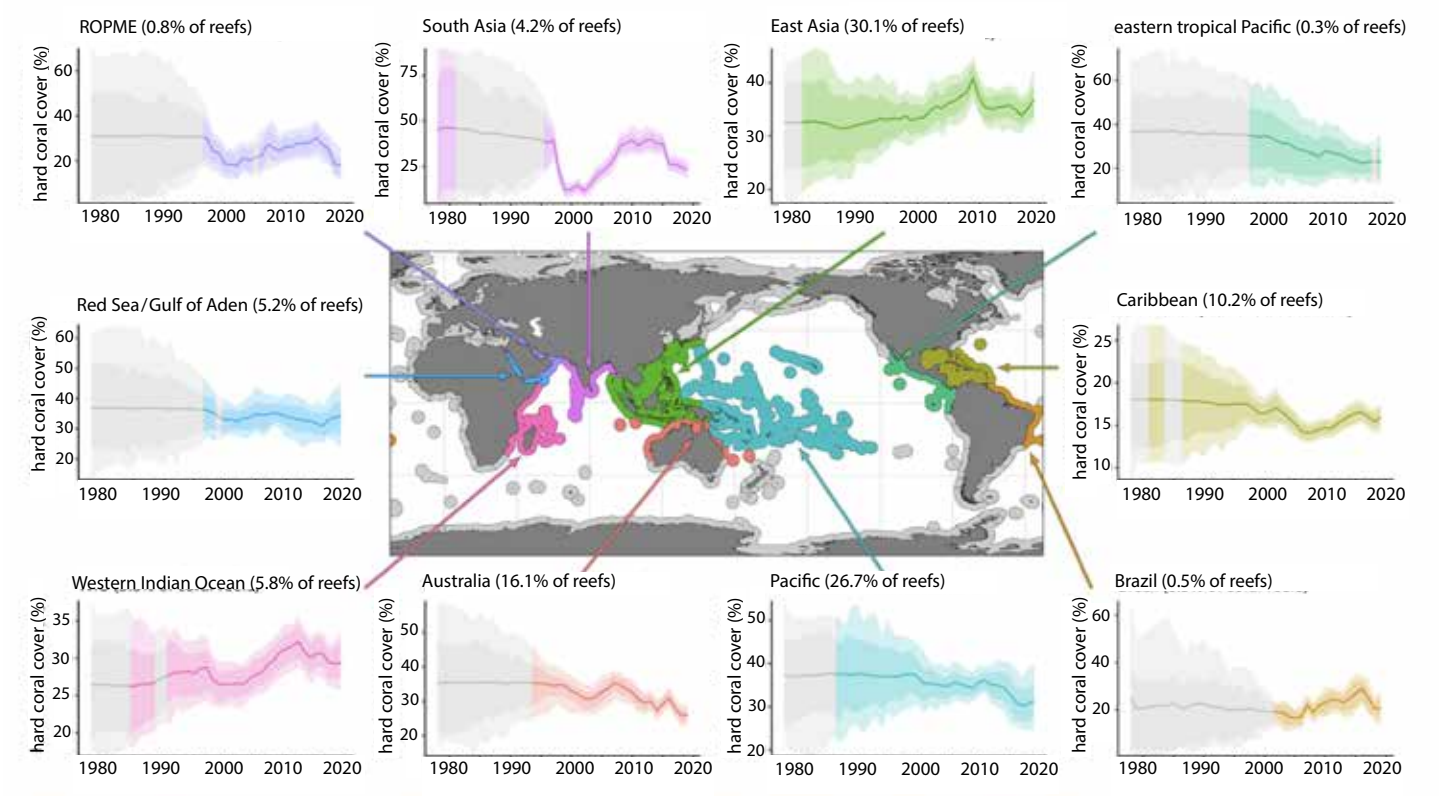
experimental heat stress episodes. My own work has included development of a bioinformatics tool to separate genes from different taxa using the RNA sequences, to examine how bacteria, archaea, viruses and fungi, for example, alter their gene expression under different environmental scenarios, expanding the suite of genes known to be associated with different stress responses.

Proteomics and metabolomics Proteomics and metabolomics represent more granular approaches to examining holobiont physiology and health in the context of disease and stress resistance, and are becoming more widely applied. Proteomics, the study of the type and amount of protein produced at a given time (which are in turn related to gene expression activity), can allow comparison of stress response not only across different populations of the same species, but among multiple species. For example, the same heat-shock proteins and antioxidants are produced across many life forms, including members of the holobiont – and therefore are examples of biomarkers that can be used to reveal why some species may be thriving while others in the same environment are not.

As an extension of proteomics, metabolomic studies can aid in further refinement of physiological processes, including the stability and degradation of proteins and lipids, and response to heat stress, e.g. the increased production of the metabolite methionine (Figure 6). Metabolomics has been used to investigate corals with SCLTD and healthy corals of the same species, examining profiles for both the coral host and the zooxanthellae, further shedding light on what may cause this disease. Such profiles of holobiont metabolites may also be used to understand susceptibility and resilience of other species to various diseases worldwide.

All together, these concepts and approaches can be applied to practices related to assisted evolution in the context of active coral-reef restoration under ongoing climate change. While the vast majority of scientists in, and tangential to, this field agree that restoration is not a silver bullet and global climate change must be immediately addressed by reducing greenhouse gas emissions, for many of us delaying interventions such as active coral restoration efforts is not an option. Until there are adequate global policies in place and atmospheric and oceanic conditions improve, restoration may be the only way in which the ecologic and economic benefits that coral reefs provide can be sustained at even the lowest levels. The last several decades have seen rapid declines in coral populations worldwide (some estimates place the global loss of living corals in recent decades as upwards of 50%) (Figure 7) and further degradation is predicted. Under business-as-usual and some restricted emissions models, 90% of the world's reef systems could die out by the end of this century. Intervention is necessary now, and it must be done in an informed manner to ensure long-term success.

Figure 7 *Long-term trends in average live hard coral cover in 10 different regions identified by the Global Coral Reef Monitoring Network. In each graph, the solid line represents the estimated mean, and the dark and light shaded areas represent the 80% and 95% confidence. ROPME = ROPME Sea Area, which is surrounded by Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates. The coloured areas and the grey areas on the map are 200 n.m. exclusive economic zones. (Souter* et al. *2020/21)*



As it has become clear that in many cases corals are not able to adapt to the pace of deteriorating ocean conditions, scientists are recognising the need to assist corals in evolving to survive these changes. While certain interactions among populations, and certain evolutionary outcomes, may occur naturally over many generations, representing decades to centuries of time, the goal of assisted evolution is to increase the pace of what may naturally take place in the wild. Continued surveying of habitats, populations, and even entire reef systems, will aid in identifying more corals that may already be resistant to common stressors such as heat stress and disease, or ones that may be able to recover when the stressful circumstances come to an end. Examining the genomes, transcriptomes, proteomes and metabolomes of these coral holobionts will allow researchers to understand the biological, physiological and molecular mechanisms behind their performance. Individuals that have undergone some or all of such profiling may be selected for further propagation and outplanting and can be cross-bred with others to increase genetic diversity and persistence of favourable traits (with the caveat that trade-offs in other traits are often common). With expanding restoration efforts worldwide, applying knowledge based on this increasingly advanced and accessible technology will alllow for better decisions to be made about such intervention and will increase probability of long-term coral-reef survival, health and service provisioning.

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*Healthy adult elkhorn coral (*Acropora palmata*) surrounded by soft corals (gorgonians) and numerous fish species offshore Grand Bahama.*

Photo: Harry Lee

The end of the line for the smallest cetacean

The vaquita is being pushed to extinction by greed and organised crime

A sea of troubles

There is no doubt that vaquitas are charismatic animals but their dolphin-like 'smile' and 'panda' eyes are not helping it attract the attention of conservationists wordwide. This is because they are found in only one place in the world – a small area at the northern end of the Gulf of California, also known as the Sea of Cortez (Figure 1). And at the start of 2022 there were probably only seven or eight of them left.

Vaquitas – a kind of porpoise (*Phocoena sinus*) – live in shallow (< 150 m), turbid waters where they feed on a variety of demersal fish species, crustaceans and squid. The vaquita ('little cow' in Spanish) was only fully described in the late 1980s, so their abundance historically is unknown, though there is a belief that they have never been particularly abundant. The first comprehensive vaquita survey took place in 1997 and estimated the population at ~ 600 individuals. By 2007, abundance had dropped to around 150, and by 2018 fewer than 19 vaquitas remained. Their depleted population would take a long time to recover as vaquitas take decades to mature, and tend to produce calves only once every two years.

An adult vaquita. In the past, vaquitas were observed in small groups of up to 10 individuals. They could be mistaken for dolphins as their triangular dorsal fins often stick out of the water (© Greenpeace/ Marcelo Otero)

Vaquitas face a number of severe challenges. They are exposed to changes in coastal habitat and pollution, and fishermen report finding whole or parts of vaquitas in the stomachs of sharks they have caught. By far the biggest threat to the vaquitas, however, is drowning after getting entangled in gillnets.

Totoaba: from local food source to the basis of organised crime

Vaquita drownings occur during illicit fishing for the totoaba (*Totoaba macdonaldi*), a large fish also endemic to the Gulf of California. Totoabas can grow to 130 kg in weight and 2 m in length, similar to the vaquita. This means that vaquitas can be caught in the mesh of the 400–800 m-long gillnets used to catch totoabas.

Totoabas may live up to 30 years, but sexual maturity is usually not reached until the fish are 6–7 years old. They were abundant and were a local food source before commercial fishing began in the 1920s, centred on the town of San Filipe (Figure 1).

The totoaba is now also endangered. It has been illegal to catch it since 1975 when it was placed on the Mexican Endangered Species List. Since then it has been added to CITES Appendix I and the US Endangered Species List, and been classed as Critically Endangered on the the International Union for Conservation of Nature's Red List.

Some groups dispute that overfishing is the cause of the totoaba's decline, and instead blame changes in the salinity in the northern part of the Gulf of California. The adult breeding population of totoabas lives for most of the year in deeper water towards the middle of the Gulf of California, but in spring moves to the Colorado River Delta, which serves as a nursery for the larval and juvenile stages. In the mid 20th century completion of the Hoover Dam and Glen Canyon Dam meant that the flow of fresh water in the Colorado River decreased dramatically, to 4% of the average flow between 1910 and 1920, greatly altering the environment in the delta, and the salinity of the northern part of the Gulf, which is now ~ 35 p.s.u. or higher. As young totoabas are metabolically most efficient in brackish water of about 20 p.s.u., this rise in salinity is considered to have contributed to the decline in the totoaba population.

To counter the fall in the totoaba population and the negative effcts on other animals, including vaquitas, gillnetting and night fishing were banned in the north-west of the upper Gulf of California in 1997 (Figure 1). These restrictions were largely ignored and insufficiently enforced. In fact, not all fishermen catch totoabas, but they are caught as bycatch in fishing for other fish and for shrimp (the most profitable legal catch), and nearly all fishermen use gillnets.

Figure 1 *The various zones of protection that could in theory contribute to protecting the vaquita: Biosphere Reserve for the Upper Gulf of California and the River Colorado Delta; gillnet exclusion zone; Vaquita Refuge (> 1800 km²), inside which is an 225 km² Area of Zero Tolerance, AZT (red) where all kinds of fishing are banned.*

'Cocaine of the sea'

The underlying reason for the decline of totoabas is the illegal export of totoaba swimbladders to China, where they are erroneously believed by many people to be effective in the treatment of a variety of health problems. The description 'cocaine of the sea' has arisen not because of any addictive properties but because of the high price the swimbladders command, and the organised crime networks, using routes already established for narcotics etc., that this illicit trade supports. 10-year-old dried totoaba swimbladders are sold for $85000 per kilo (2021 figures).

Despite being illegal, the swimbladders were often traded openly and traders reported being warned of imminent checks by Chinese authorities. Mexican and Chinese authorities then tightened checks, and raids resulted in confiscations of large numbers of swimbladders and several arrests. The situation has improved somewhat thanks to increased awareness of the issue in China and better cooperation with the United States, through which many swimbladders pass on their way to China.

Between the beginning of 2018 and April 2019, Chinese customs authorities uncovered five cases of smuggling of totoaba swimbladders. Thirty-two people were arrested and $45 million worth of swimbladders were seized. At the same time, Earth League International (ELI) were running an intelligence gathering operation called Operation Fake Gold, during which the entire illicit totoaba swimbladder supply chain, from Mexico to China, was mapped and investigated. Thanks to information that ELI shared with the Mexican authorities, in November 2020 a number of high-profile totoaba poachers and traffickers were arrested.

Totoabas are an important source of revenue in an area where fishing is the main way of life, but a poor fishermen in San Felipe would make only a tiny fraction of the final price of the swimbladders. There is hostility between the ordinary fishermen and those involved in the trade in totoabas (who are often in debt to the cartels) and a toxic atmosphere prevails in the town. In a 2021 interview with the BBC, Ramón Díaz, President of the San Felipe Fishing Federation, said of the totoaba: '*We used to catch it in the 60s and 70s. Then the Chinese came with their suitcases full of dollars, and bought our consciences. ... Organised crime has stolen the Sea of Cortéz.*'

Attempts to save the vaquita

In 2005 a Vaquita Refuge, where all commercial fishing was banned, was declared in the core area of the vaquita's range; more recently (2020) a Zero Tolerance Area (ZTA) where all fishing is banned (Figure 1) was declared within the Refuge. Restrictions were generally ignored and on a given day in the totoaba season dozens of small boats, mostly unlicensed, could be seen heading into the gillnet exclusion zone.

Prior to the setting up of the ZTA the Mexican government, international committees, scientists and conservation groups came up with various plans to reduce the use of gillnets, and promote population recovery of both vaquitas and totoabas – all without much success.

Governmental efforts

In 2008 Mexico launched a programme called PACE-VAQUITA in an effort to enforce the gillnet ban in the Biosphere Reserve (Figure 1), to enable fishermen to exhange their gillnets for vaquita-safe fishing gear, and provide economic support to those surrendering fishing permits and pursuing alternative livelihoods. Some progress was made with legal fishermen, but hundreds of poachers continued as before.

After PACE-VAQUITA ended in 2015 the Mexican government distributed 3000 13 m-long *suripera* shrimp nets that allow vaquitas, dolphins and turtles to escape. But fishermen complained these reduced their catch by 80% – a significant problem in a region where there are few other ways of earning a living – and only a small group of them were brave enough to be seen to be cooperating with the authorities. The Mexican Museo de la Ballena (Whale and Marine Science Museum) also supported a small group of fishermen interested in ending reliance on gillnets, and sponsored alternatives to fishing like oyster cultivation.

In April 2015, Enrique Peña Nieto, the President of Mexico, announced a programme of rescue and conservation for the vaquita and the totoaba, including closures and a partial gillnet ban, and financial support to fishermen in the area. In 2017 a permanent gillnet exclusion zone was declared in the upper Gulf (Figure 1).

Other more innovative methods were also considered. In 2017, the Mexican government planned to use dolphins (trained by the US Navy to search for missing scuba divers) to find vaquitas and herd them into the Refuge. Another idea, proposed by the International Committee for the Recovery of the Vaquita (CIRVA) was to remove some vaquitas from the intensive fishing area and release them in protected sea pens. Two vaquitas were captured but both suffered from shock; one died shortly after capture, and the other was released.

The challenge for NGOs

Few NGOs work in the area: they are seen as outsiders and are generally unpopular, and within the town there is hostility towards local people who cooperate with them. Nevertheless, local and international conservation NGOs, including the Mexican Museo de la Ballena and the US-based Sea Shepherd Conservation Society, have been working with the Mexican Navy to spot fishing in the Refuge and remove illegal gillnets. This heightened the tension between locals and conservationists; gillnets are expensive, and fishermen say they have not received any compensation from the federal government for loss of income due to restrictions on where they can fish. When operating within the Vaquita Refuge, Sea Shepherd's vessel *Farley Mowat* has several times been attacked by large numbers of poachers throwing rocks, lead weights and Molotov cocktails.

Matters were not improved when in December 2020, a fisherman was fatally injured and another seriously hurt after their fishing boat collided with Sea Shepherd's *Farley Mowat* which was out taking up gillnets. There was a riot in San Felipe: the Museo de la Ballena's ship *Narval* was damaged, and one of the Mexican Navy's patrol boats was set alight.

Sea Shepherd and the workers from the Museo de la Ballena were forced to withdraw from the area. This situation lasted just over seven months, time that was used by the *totoaberos* to catch the fish during their breeding run between January and April; March is the peak of the totoaba poaching season when entanglement risk to vaquitas is greatest.

After seven months, the *Narval* was back removing gillnets from the Zero Tolerance Zone, supported by a grant from UNESCO's Rapid Response Facility (RRF)* which allowed the crew of the *Narval* to be paid for a month. Sea Shepherd also resumed work, but again faced violence.

Recent developments

The ZTA had been slightly enlarged in September 2020, but after the Sea Shepherd incident, the Mexican government considered lifting the totoaba's endangered status, and legalising other fishing already taking place in the Refuge. Then in February 2021, the Secretariat of Environment and Natural Resources announced that it may reduce the size of the Refuge, as the vaquita was unlikely to ever reoccupy its historical range.

*The RRF is supported by the Fondation Franz Weber, Arcadia, Fondation Iris and the Government of Norway.

Totoabas being inspected by a diver in one of Earth Ocean Farm's submersible cages. Such cages are challenging to operate but provide the fish with a more stable environment, and are better protected from storms and the infectious stages of parasites.

The situation was not helped by claims that the change in salinity resulting from the building of the dams was causing the vaquitas to suffer from osmoregulation failure and that this, along with shark predation, had more effect on the vaquita population than fishing.

The IUCN Species Survival Commission swiftly responded by sending a refutation of these ideas to the Secretaries of the Mexican Navy, Environment and Agriculture and Fisheries authorities. An Annex to the letter stresses that being marine mammals, vaquitas naturally eliminate excess salt; also that there is no evidence that vaquitas are maladapted to their current habitat; animals are healthy with no signs of being nutritionally stressed, and females still produce calves. The Annex also provides evidence to show that predation by sharks is very unlikely and says that *'There is every reason to believe that if vaquitas were immediately protected from gillnets, throughout the species' range and particularly in what is called the Zero Tolerance Area (ZTA), the population could recover.'*

Then in July 2021 the Intergovernmental Group for Sustainability in the Upper Gulf of California effectively abolished the ZTA by replacing the fishing ban with a number of 'triggers' based on how frequently illegal fishing boats are detected in the ZTA. For example, fishing should be banned over an area wider than the ZTA for seven days if 60 illegal boats have been detected in the area three times in one month. Observations from sea by Sea Shepherd, and from land by a group called ZTA Watch, confirm that (unsurprisingly) the new rules have not been enforced and are regularly violated.

In June 2022 the Mexican authorities began a controversial plan to drop 193 concrete blocks wth hooks embedded in them onto the sea bed of the ZTA, to snag illegally deployed gillnets. It is not clear how, or whether, any snagged gillnets will be recovered, and a gillnet that remains near the bottom will continue trapping vaquitas and other animals indefinitely.

Good news for totoaba populations

Although discarded by poachers, totoaba meat is becoming highly appreciated for its flavour and texture. Totoabas are well suited to aquaculture, as they grow relatively fast and reach a commercial size of 3 kg in only 18 months; furthermore their natural schooling behaviour means they adapt well to being penned.

A research team at the State University of Baja California (UABC) were the first to successfully spawn totoabas in captivity. They supply juvenile totoabas to a number of aqauculture enterprises, of which the newest is Acuario Oceanico, which owns a concession off San Filipe.

Earth Ocean Farms (EOF), an aquaculture enterprise off La Paz, California Sur (off the bottom of the map in Figure 1) produces juvenile totoabas from its own hatchery. In March 2022 EOF were given permission by the CITES Standing Committee to sell totoabas (but not swimbladders) to markets outside of Mexico. In particular, this would open up trade with the US which in 2020 had banned the import of shrimp and other seafood caught in vaquita habitat. This relaxation of rules is significant for the commercial viability of totoaba farming.

It is also relevant to the viability of the wild totoaba population, as apart from selling farmed totabas which would otherwise come from the wild, EOF, along with other aquaculture businesses and UABC, release thousands of young totoabas into the Gulf annually. To ensure that genetic diversity is maintained in the wild population, the number of releases is carefully controlled, and genetic markers are used to ensure that released totoabas come from different families. Genetic monitoring of totoabas taken from the wild has confirmed that released totoabas are now producing young of their own.

It is striking that EOF have managed to involve and enthuse local people, particularly by involving them in the release of juvenile totoabas. By contrast, fishermen in San Filipe felt excluded from decisions that significantly affected their livelihoods. But even with local cooperation, there is a need for both enforcement of rules and sufficient compensation for those whose livelihoods are lost as a result.

Is the vaquita doomed anyway?

Now that there are so few vaquitas left, there is an assumption that inbreeding means that there is no hope of a return to a healthy population. But research published in *Science* by Robinson *et al*. in May 2022 indicates that this is not the case.

The group sequenced and examined 20 vaquita genomes to determine the genetic variability in the population and estimate ancestral population size. They found that the long-term population size of vaquitas has been low (for a marine mammal) with approximately 1000 years of stable genomic diversity. Genomic comparisons with other cetacean species, and modelling, indicated that vaquitas are unlikely to suffer from problems resulting from inbreeding.

Simulations using knowledge of the vaquita genome suggest that it can recover if bycatch mortality is immediately halted. Hope comes from the classic, extreme example of the Chatham Island black robin, whose population recovered from a single breeding pair in the 1980s to hundreds of individuals, but only with intensive conservation efforts.

This study provides hope for vaquitas and other naturally rare endangered species and highlights the value of genomics in predicting extinction risk. Meanwhile, in San Felipe, some see the vaquitas as the enemy; others say that vaquitas don't actually exist. They might soon be right.

Ed.

A selection of the sources consulted for this article:

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